5-2004

The Effect of a Supplemental Air Distribution System on Greenhouse Tomato Production

Samuel Jason Ray
University of Tennessee, Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Samuel Jason Ray entitled "The Effect of a Supplemental Air Distribution System on Greenhouse Tomato Production." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Michael J. Buschermohle, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Samuel Jason Ray entitled "The Effect of a Supplemental Air Distribution System on Greenhouse Tomato Production." I have examined the final paper copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Michael J. Buschermohle, Major Professor

We have read this thesis
and recommend its acceptance:

James B. Wills, Jr.

R. Allen Straw

Accepted for the Council:

Vice Provost and Dean of Graduate Studies

The Effect of a Supplemental Air Distribution System on Greenhouse Tomato Production

A Thesis Presented for the Master of Science Degree
The University of Tennessee, Knoxville

Samuel Jason Ray
May 2004

DEDICATION

This thesis is dedicated to Hubert (Lynn) Vanzant. Through his love, support, and guidance, he has revealed to me the blessedness of the bond between a man and the land.

ACKNOWLEDGMENTS

The author wishes to express sincere appreciation to Dr. Michael J. Buschermohle for his mentorship, advice, and support through the duration of the project. Special thanks are also extended to the other committee members for their significant contributions to this research, as well as for their friendship and support. They include James B. Wills, Dr. Richard A. Straw, and Dr. D. Raj Raman. Mr. Wills made this study possible by authoring a proposal and successfully obtaining grant money. He was also heavily involved in all aspects of the research, from offering technical assistance to harvesting tomatoes. Dr. Straw was consistently eager to offer advice on cultural practices and pest control. Dr. Raman was enthusiastic to offer ideas for technical content and assistance with editorial issues.

An enormous appreciation is also expressed to Gary Honea. He has spent endless hours in the greenhouses repairing equipment, maintaining of plants, and harvesting and marketing produce. During the absence of others, Mr. Honea was always there to take care of things. He also provided technical consultation over the course of the study.

Thanks is also extend to Dr. John Hodges, Superintendent of the Knoxville Experiment Station (KES), for providing the test site at the Plant and Soil Science Farm to conduct this research. Gratitude is also expressed to the KES personnel, who were always available to lend a hand in maintaining and harvesting the tomato crops.

Sincere thanks is also extended to Dr. Carl Sams and David Smith for their technical assistance. They never hesitated to take time to offer their expertise. Appreciation is express to Dr. William Hart for the use of his laboratory and tools to assemble the experimental prototype. Also, thanks is extended to Wesley Wright for providing weather data.

The student workers included William Pinson, Miles Ledbetter, Jr., Haizhou Li, Robert Atchley, and Bryan Biss. Their assistance in maintaining the crops was invaluable. Several other students also offered assistance during periods of heavy harvesting, and their help is greatly appreciated.

Appreciation is also extended to Dr. Ron Yoder, Head of Biosystems Engineering and Environmental Science, who provided transportation for production delivery.

Lynn Vanzant and Karl Smith were invaluable in their help to distribute the yield to consumers.

A huge appreciation is extended to the USDA and the Tennessee Fruit and Vegetable Association for funding this research.

Lastly, the author expresses loving appreciation to his wife, Michelle, and to his parents, James and Patricia Ray, for their endless love and support.

ABSTRACT

The effectiveness of a supplemental internal air distribution system for closed greenhouses with dense plant canopies was evaluated. The system employed centrifugal fans and perforated ducts to move relatively warmer air from above the canopy to within the canopy. Preliminary tests demonstrated the potential to improve net profits in commercial tomato greenhouse production by increasing yield and accelerating fruit maturity. It was hypothesized that reductions in temperature and humidity variations contributed to reduced disease susceptibility. The purpose of this project was to determine the validity of the preliminary results by testing the effectiveness of the system in a controlled experiment.

Two 270-m^2 greenhouses, a treatment house and an identical control house, were constructed. A fall tomato crop from August to December 2002 and a spring crop from January to July 2003 were evaluated. Electricity and fuel consumption were separately metered for each house. The same variety of beefsteak tomato (*Lycopersicon esculentum* Mill cv. Trust) at identical growth stages was placed in each house on the same day. Set points for thermostats controlling ventilation and heating were also identical in both houses. Relative humidity, temperature, carbon dioxide concentration, and light intensity were logged in identical locations in each house. All harvested tomatoes were graded and weighed.

During the first crop grown in the newly constructed greenhouses, several start-up problems were addressed in the equipment, structures, and cultural practices. Because of

these start-up issues, the environmental and yield results for the fall crop were questionable. In contrast, the spring data was considered reliable.

During the spring season, the bulk of environmental differences between the houses occurred at night. Vertical and longitudinal thermal gradients were significantly less in the treatment house during the first half of the growing season. Reduced vertical and longitudinal relative humidity gradients were also observed in the treatment house during nighttime for most of the growing season. The north side of the control house experienced relative humidity (rh) levels from 95 to 100% from March to the end of the season, while the treatment house generally remained drier, at 90 to 95% rh. An elevated carbon dioxide concentration was found in the treatment house during nighttime hours, which is hypothesized to be due to higher respiration rates. The fuel consumption in the treatment house was reduced by 9%, resulting in a fuel savings of $177, while the electrical consumption followed the opposite trend. The treatment house used 3,550 kWh ($243) more electricity than the control house, primarily to supply power to the supplemental air distribution fans. The treatment house yielded 14 % (518 kg) more marketable fruit than the control. At a wholesale price of $2.20 per kg, the difference in yield returns was $1140 per year (assuming one crop per year). Amortized capital cost of the system was estimated to be $178 per year, based on 5 years at 10%. The net benefit of the system was therefore estimated to be $896 per year.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1 – Introduction

Justification

The ability to control the environment and obtain premium prices for off-season tomatoes are the driving reasons for the increasing popularity of greenhouse tomato production. Over the past decade, the area under plastic in Tennessee dedicated to tomato production has swiftly increased. Today, Tennessee producers grow 16 to 20 hectares of greenhouse tomatoes and harvest approximately 20 kg/m^2 per growing season (Straw, 2003, Pers. Comm.).

Despite the increasing trend of production, the vast majority of Tennessee's off-season tomatoes found in the market are field-grown tomatoes imported from Florida, California, or Mexico. Mass production drives the price of the imported tomatoes down, but taste is usually compromised. Though the fruit may look appealing, the internal quality is lacking compared to a vine-ripened greenhouse tomatoes from a local producer (Bauerle and Short 1984). Consumers view greenhouse tomatoes as locally grown, fresh, and flavorful and are willing to pay as high as three times the price of imported field-grown tomatoes (Kamberg 1997). Lucier et al. (2000) estimate the national annual consumption of fresh tomatoes to be 8.6 kg per person. Assuming that consumption is uniform throughout the year and that consumption in Tennessee is near the national average, then greenhouse growers are supplying roughly 30 to 40% of the demand in Tennessee over an estimated harvest period of 2 ½ months (typical spring harvest period). This estimate reveals a considerable market potential for the growth of the greenhouse tomato industry in Tennessee.

Though many Tennessee tomato producers are experiencing the advantages of growing in greenhouses and are aware of the potential market, there are still major hurdles preventing optimum yield. Disease and fruit abortion are primary reasons for yield losses. Many factors may contribute to the plants' susceptibility to harmful pathogens; air temperature and humidity are among the most prevalent. Temperature and humidity are also key factors in fruit abortion. If the temperature gets too low or too high and/or the air moisture begins to condense on the foliage, then blooms are threatened. With proper air circulation, ventilation, and heating, the negative impacts of these factors are considerably reduced. However, as the plant canopy becomes dense, proper air circulation becomes a major issue, especially in the cooler season when the ventilation fans are rarely operating. The dense foliage inhibits air movement, so the air becomes stagnant. It was hypothesized that as the plants transpire, the air within the canopy becomes more humid, the dry-bulb temperature decreases, and carbon dioxide depletes during photosynthesis. This is thought to produce a vertical stratification of temperature, humidity, and CO_2, and the plants would become highly vulnerable to fungal disease and fruit abortion.

The goal of this study was to determine the effectiveness of a system designed to improve the air distribution in greenhouses with dense tomato plant canopies. To achieve this goal, four specific objectives had to be accomplished. The first was to obtain environmental data over time within and above the canopies in the treatment and control houses for the duration of both fall and spring growing seasons. Factors measured included air temperature, relative humidity, carbon dioxide (CO_2) concentration, and light intensity. The second objective was to acquire yield and grade data for each season. The third objective was to use the environmental data to understand any yield trends and explain why any difference in yield existed. The final objective was to determine the economic impact, if any, of the system. To do this, an economic analysis was conducted.

Review of Literature

Temperature Effects

Achieving an optimal range of temperature and humidity levels is essential for maximizing yield for any greenhouse crop. Desired temperature and humidity ranges for tomato production have been studied extensively.

Temperature is the most important factor influencing plant development, such as leaf formation, anthesis, and fruit set (Landsberg 1975; Cockshull 1992). Optimum temperatures for greenhouse tomato production have been divided into daytime and nighttime regimes. Witter and Aung (1969) reported that the optimal ranges for greenhouse tomato production are from 15 to 18 °C at night and 18 to 27 °C during the day, depending on irradiance, variety, etc. Similarly, Went and Cospar (1945) claimed that nighttime temperature is the critical factor influencing fruitset and that the optimum range is 15 to 20 °C. Previous research by Willits and Peet (1998) showed that both yield and fruit quality are highly affected by mean nighttime temperatures. Findings from their study revealed that nighttime temperatures above 21 °C compared to temperatures below 20 °C reduced fruit set by 39% and the total yield by 53%. The cooler treatment also increased the number of No. 1 fruit (highest quality) and the total weight of No. 1 fruit by 85% and 106%, respectively. However, Peet and Bartholemew (1996) showed that the rate of fruit development increase with nighttime temperatures, evaluating from 18 to 26 °C.

Air temperature also affects pollination. Dane et al. (1991) noted a drastic reduction in pollen fertility at prolonged periods of high temperatures, reaching 35 to 38 °C during daytime, and 20 to 23 °C during the night. Charles and Harris (1972) showed a decline in pollen germination as temperatures increased from 20 to 27 °C.

Humidity Effects

Though humidity is not as influential on growth and development as temperature, it is not to be overlooked. It is common for researchers to quantify the air moisture in relation to the plant in terms of vapor pressure deficit (VPD) because it is a direct indicator of the driving force for transpiration. The plant is assumed to be at saturation while the amount of vapor in the air varies. If the VPD is too high, above 1.0 kPa (57% rh at 20 °C) , extremely high transpiration rates occur, and plant growth is reduced in most horticultural crops, because photosynthesis is hampered by a decrease in stomatal conductance (Hoffman 1979). For example, Leonardi et al. (2000) reported a reduction in overall tomato yield and degradation in quality as the VPD increased from 1.6 to 2.2 kPa (31 to 6% rh at 20 °C). However, complications also occur when the VPD is too low. Moroto et al. (1995) found a higher degree of cracking (mostly radial) in tomatoes exposed to a range of VPD from 0.1 to 0.0 kPa (96 to 100% rh at 20 °C) compared to those exposed to a range of 0.4 to 0.7 kPa (83 to 70% rh at 20 °C). Pollination is also inhibited at high humidity levels because of the insufficient number of pollen grains reaching the stigma (Tuzel 1999). Bakker (1990) reported calcium deficiencies and reduced leaf areas in plants exposed to lengthy periods of high humidity. He claimed that humid conditions also resulted in a loss of mean fruit weight, as well as a poorer keeping quality. In his study, lower VPD values of 0.72 kPa day/0.57 kPa night (76% rh at

24 °C / 72% rh at 18 °C) compared to higher VPD values of 0.62 kPa day/0.25 kPa night (79% rh at 24 °C / 88% rh at 19 °C) resulted in an 8% increase in yield in a beefsteak variety tomato. Grange and Hand (1987) concluded that 0.7 to 0.5 kPa (70 - 78% rh at 20 °C) is the optimum range for the VPD.

Aside from the previously mentioned direct growth responses, humidity is also correlated to the viability of fungal diseases, many of which require free water on the foliage to germinate (Bakker 1995). Gray mold (*Botrytis cinerea*) is among the most common in greenhouse tomatoes, which is promoted by cool, humid conditions and poor ventilation (Dodson et al. 1997). O'Neill et al. (1997) stated that infection and sporulation occur when air temperatures are between 5 and 26 °C, with the most rapid development at 15 °C. The most severe cases of gray mold result in the loss of the entire crop. Powdery mildew (*Odium lycopersici*) is another common fungal disease typically infesting greenhouse tomato plants. Unsprayed plots have been reported to experience 40% yield losses due to powdery mildew (Jones and Thomson 1987). Guzman-Plazola et al. (2003) found that powdery mildew did not germinate above 30 °C and disease progression was significantly greater at 20 °C than 25 °C. They also state that disease progression was greatest at relative humidity levels of 50 to 70% rh and that spore germination also occurs between 80 and 90% rh, but the progression of the disease was limited by prolonged exposure to the high humidity levels. Whipps and Budge (2000) found that powdery mildew is less prolific as the relative humidity rises from 80 to 95% at 19 °C.

Internal Air Circulation

It is typical for heaters and ventilation fans to be controlled by thermostats at a single fixed location in the greenhouse, but hurdles must be overcome to achieve a uniform distribution of the set point temperature throughout the greenhouse. Several researchers have documented the importance of circulating internal air in greenhouse production. The purpose is to achieve a homogeneous temperature, humidity, and CO_2 distribution within the growing environment. Germing (1967) stated that continuous air movement is vital to reduce horizontal and vertical temperature gradients. Air movement is also helpful in pollination and distributing fumigants from pesticidal bombs.

Several air circulation techniques have been studied and evaluated for various combinations of greenhouse structures and crops. Walker and Duncan (1974) summarized the most common techniques to distribute air throughout the environment: 1) vertical convections; 2) horizontal convection; 3) sidewall ventilation; 4) single overhead perforated plastic sleeve; 5) two overhead perforated plastic sleeves; 6) ground perforated plastic sleeves. Vertical convection uses air-mixing fans in the gable of the house to blow air along both sides of the roof and down the sidewalls to the floor. Horizontal convection uses horizontal airflow fans (HAF) located above canopy level on both sides of the greenhouse to circulate the air horizontally. Sidewall ventilation utilizes a unit on the sidewall to force air toward the roof, which then moves down the opposite sidewall and along the floor back to the unit. A single overhead perforated plastic sleeve (polytube) usually has a row of perforations on each side of the tube, which discharge air again down the roof and sidewalls to the floor. Sometimes two overhead tubes are used rather than one, which cause two rotational airflow patterns in a cross-section. Lastly, multiple perforated plastic sleeves along the ground were used to distribute air, commonly between crop rows. Walker and Duncan (1974) tested the effectiveness of each method in a greenhouse that had negligible canopy mass. An acceptable minimum airflow velocity of 12.2 m/min at all points in the greenhouse was established, which was considered to ensure thorough mixing (Walker 1967). They found that the HAF fans distributed acceptable airflows throughout greenhouse area, and the best results occurred when the fans were tilted 15° towards the center of the house. Acceptable results were obtained with the sidewall ventilation and using two overhead perforated plastic sleeves. Inadequate airflows were obtained with vertical convection and the single overhead and ground perforated ducts.

Acceptable flows are currently reported in terms of air exchanges (greenhouse volume of air) per unit time rather than air velocity, and the acceptable minimum is 15 to 20 air exchanges per hour (ASAE 2002). Buschermohle and Grandle (2002) stated that the two methods that have become the most widely accepted practice for distributing internal air are the horizontal convection with HAF fans and the overhead perforated plastic sleeve. They recommended that the HAF fans be 12 to 15 m apart along the length of the greenhouse and 1/4th of the width of the greenhouse from the sidewall. The authors claimed that the benefits of continuously running these fans outweigh the additional cost of electricity. However, since the airflow is typically parallel with the crop rows, air tends to flow in the path between the plants rather than through the plants, which causes lower temperatures to occur inside the canopy (King 1962).

The overhead polytube system typically performs three functions. First, it continually mixes the air. Secondly, heated air is blown directly into the intake, and the tube distributes the warm air along the greenhouse. Lastly, an axial fan forces fresh air from outside through the tube during ventilation. Wells and Amos (1994) outlined procedures to determine the duct diameter and perforation size and spacing, which depend on the fan selection and the scale of the greenhouse. They recommend the static pressure along the duct to be as uniform as possible, and in range from 25 to 100 Pa. If the pressure is too low, the duct will not properly inflate, but if it is too high, excess energy is expelled. Researchers have addressed the concern of the decreasing temperature of the discharging air along the duct (overhead or at ground level). Bailey (1973) explained that heat transfers from the air inside the duct to the air surrounding the duct and suggested that higher flowrates would reduce the temperature drop. The severity of the temperature drop was demonstrated by Menses and Monteiro (1990), who measured a drop from 34 °C to 12 °C over 60 meters of duct length using a single overhead polytube, with the ambient temperature approximately 10 °C. This drop resulted in a net longitudinal temperature gradient of ~2.0 °C per 64 m in the tomato plant canopy, most of which occurred in the latter half of the distance along the house. The airflow rate was 12,000 m^3/hr, which only provided less than 10 air exchanges per hour. The relatively small change of temperature across the length of the canopy was probably attributed to the low exchange rate. They suggested that this could be reduced using perforated tubes at ground level, because heat transfers from the overhead ducts to the roof. A temperature drop of only 3 to 3.5 °C was found with multiple tubes on the ground over a length of 15.8 meters (Teitel et al. 1999). Negligible vertical and transverse gradients were found with either the overhead or ground level polytube systems (Meneses and Monteiro 1990;

Teitel et al. 1999), but this ground level study was conducted in a rose canopy, which is considerably less dense than a mature tomato canopy.

The challenge presented to an air circulation system is greater in the fall crop than in the spring crop, because the growth stages of tomato plants differ between the spring and fall crops with respect to the seasonal temperatures and sunlight intensities. During the fall season, the canopy mass increases and matures as the seasonal temperature and sunlight intensity decrease. The majority of the fruit set period occurs from August through October while light intensities are high and outside temperatures are warm to mild. During this period, little to no supplemental heating is required. The bulk of the harvest or ripening period occurs during periods of low light intensity from early November through December while outside temperatures are cool to cold. During this period, supplemental heating is substantial.

The opposite occurs during the spring when the canopy mass increases/matures with seasonal temperatures and sunlight intensity. Outside temperatures are cold to cool during the fruit set period from February through April, and supplemental heating is considerable. Little to no supplemental heating is required during the harvest or ripening period from May through July when outside temperatures are warm to hot, and sunlight intensities are high.

Larger temperature gradients in greenhouses are expected during periods when supplemental heating is required, so the temperature gradients with respect to plant maturity differ considerably between fall and spring crops. Most of the stratification is expected to occur during the ripening period of the fall crop and the fruit set period of the spring crop.

Objective

Several studies have explored optimum temperature, humidity, and carbon dioxide levels for tomato production. A considerable amount of research has also been conducted in determining the effectiveness of various types of internal air distribution systems in minimizing temperature and humidity gradients within greenhouses. Work has also been performed on evaluating the use of multiple perforated polytubes to deliver heated air within the canopy (Teitel et al. 1999), but one or two large fans were used to supply a header, which distributed air to each tube. The header employed by Teitel et al. (1999) can be a hindrance in routine greenhouse operations and can be expensive and complex to install. However, no work has been done on using multiple independent blower/duct systems to deliver air within a tomato canopy to supplement an existing HAF system. The objective of this study was to implement and evaluate the effectiveness of a system in which a single fan and duct would be used per double row to force air from above a tomato canopy to within the dense foliage. This type of simple, inexpensive, and convenient system could be installed in existing structures without requiring extensive modifications, and it may increase yield and decrease fuel consumption. Both a fall and a spring season were to be evaluated and compared. It is hypothesized that the supplemental air distribution will be more effective, from a temperature perspective, during heating modes when temperature gradients are expected to be the greatest. The efficacy of the system may differ between fall and spring seasons due to differences in the ratio of temperature to canopy development between seasons.

Additionally, it is suspected that CO_2 gradients occur across the canopy boundary, but a lack of research is evident that quantifies the degree of stratification. This quantification was an additional outcome of this study.

Chapter 2 – Materials and Methods

Test Site Description

The experiment was conducted at the Knoxville Experiment Station in Knoxville, Tennessee (36° lat., elev. 290 m). Two identical double-layer plastic quonset greenhouses served as a control and a treatment during the study periods. The greenhouses were longitudinally oriented north to south and were 3 m apart from one another. Three smaller greenhouses not included in the experiment were on the western side of the test houses, also 3 m apart from one another (Figure 1). The test greenhouse on the western side served as the treatment house during the fall, and the eastern greenhouse was used as the treatment during the spring.

Each house was 9.1-m wide by 29.3-m long with 1.5-m sidewalls. The center was 4.3 m above the ground. Each house was equipped with two 39-kW propane unit heaters (Reznor Model FE, Thomas and Betts Corp., Mercer, PA) mounted 2.4-m high in opposing corners. One small (61-cm dia.) and two large (122-cm dia.) exhaust ventilation fans were located on the southern wall (Figure 2). One of the large fans was a 2-speed fan (Coolair Model NBF48K, American Coolair Corp., Jacksonville, FL), providing a maximum airflow rate of 545 m^3/min at 12 Pa and was mounted on the eastern side. The other was a single speed fan (Coolair Model NBF48L, American Coolair Corp., Jacksonville, FL), delivering an airflow rate of 545 m^3/min at 12 Pa and was mounted on western side. The small fan (Coolair Model NBF24J, American Coolair Corp., Jacksonville, FL) was located just under the ridge bar and delivered an airflow rate of 191 m^3/min at 12 Pa. The fans were capable of providing five levels of ventilation ranging from 0.20 to 1.35 exchanges/min. Louvers were located on the north end of the

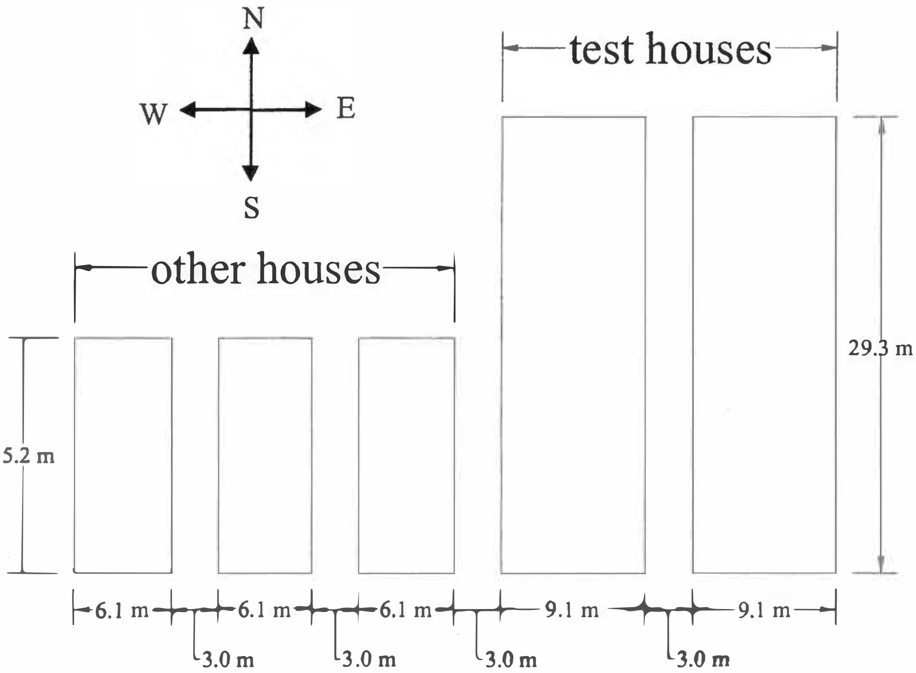


Figure 1. Orientation and dimensions of test greenhouses and other neighboring greenhouses.

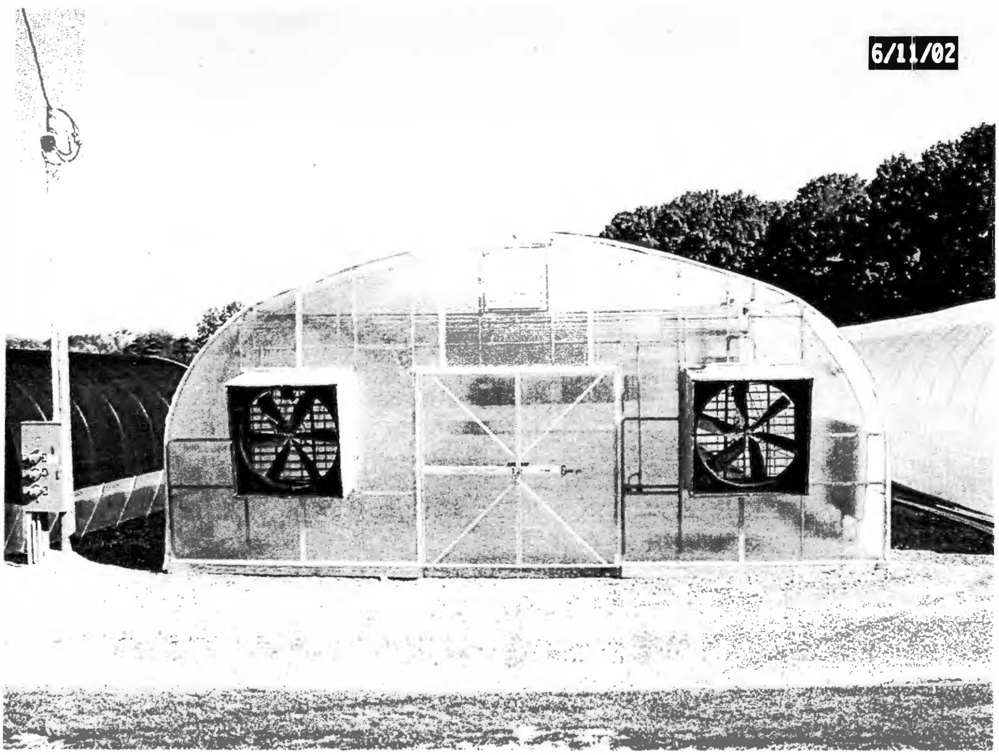


Figure 2. Ventilation fans on southern side of greenhouse.

greenhouses, which were automated to open as needed during ventilation. Four horizontal airflow fans (Uni-Flo 2000 Model 4EQ0020, Uni-Flo) in each house circulated the internal air. Each HAF fan provided airflow at 57 m^3/min, which equated to 15 air exchanges per hour, which met the acceptable minimum exchange rate (ASAE, 2002). Each house was also equipped with an evaporative cooling pad (1.2 m x 7.3 m) on the north wall.

Crop Description

The test periods were from August 8 to December 18, 2002 for the fall crop and from January 28 to July 7, 2003 for the spring crop. The historical weather data for the nearest National Weather Service Station, Knoxville, TN, is presented in Table 1. Seeding the tomato plants (*Lycopersicon esculentum* Mill cv. Trust – beefsteak variety) was accomplished in a greenhouse. The seedlings were transplanted when they were 20- to 30-cm high. A nylon string hooked to a high-tensile wire supported each individual plant. Wooden posts between the single rows supported the wire. There were five double rows of tomatoes and a total of approximately 700 plants per house. Bumblebees (*Bombus terrestris*) were used for pollination.

Irrigation

Each double row shared a common water line, and a supply tube with a spray stake delivered water to each individual plant. Irrigation timing was controlled with an automated system (Solar-Gro 12 Model 6W012, Davis Engineering, Winnetka, CA) based on accumulated solar radiation. Water requirements were calibrated to the need of the plants throughout the season based on recommendations from a crop specialist.

Table 1. Historical weather data for Knoxville, TN obtained from the National Weather Service.

	Temp. (°C)	Relative Humidity (%)		Extreme Temp. (Days Per Month)		Rain (cm)	Cloudiness (Days Per Month)		
	Avg	A.M.	P.M.	Below 0 °C	Above 32 °C	Avg	Clear	Partly Cloudy	Cloudy
January	2.2	82%	64%	20	0	10.7	6	7	18
February	4.5	80%	60%	16	0	10.4	7	6	16
March	9.4	80%	55%	9	0	13.0	7	7	16
April	14.2	82%	52%	2	N/A	9.4	8	9	13
May	18.6	87%	57%	N/A	1	10.4	8	10	13
June	22.9	89%	59%	0	5	10.2	7	12	10
July	24.8	90%	61%	0	11	11.9	7	13	11
August	24.4	92%	60%	0	9	7.9	8	12	10
September	21.2	92%	59%	0	3	7.9	10	9	11
October	14.7	90%	55%	1	0	7.1	12	8	11
November	9.3	85%	59%	8	0	9.7	9	7	14
December	4.5	83%	64%	17	0	11.4	7	7	17
Annual	14.2	86%	59%	72	29	119.6	97	107	162

Fertilizer solutions and nitric acid were dosed into the bulk water supply with injectors (Model DI16, Dosatron International, Inc., Clearwater, FL) at a fertilizer solution / water ratio of 1:100. The amount of fertilizer applied was based on the modified Steiner recipe. The fertilizer solution ratios for the fall and spring seasons are shown in Table 2. The pH was maintained close to 6.0.

Environmental Control

Heating and cooling systems were controlled by thermostats (Models T19PC-single pole/single throw and A28PJ-single pole/double throw, Johnson Controls, Milwaukee, WI). All thermostats were located 1.2 m from the ground in the center of the houses and were engulfed in the canopy as the season progressed. Each heater was controlled by an independent thermostat. During the fall, both heaters in each house were

Table 2. Mixture ratios for fertilizer solutions for fall and spring seasons based on the modified Steiner recipe.

Season	Growth Stage	Fertilizer Mixing Ratio (kg of fertilizer per 150 liters of water)			
		4-18-38 (N-P-K)	$MgSO_4$	$Ca(NO_3)_2$	KNO_3
fall	from transplant to 1st bloom on	5.0	2.3	4.5	1.8
	from above until end of crop	10.4	5.0	9.1	2.7
spring	from transplant to 1st bloom on	4.6	1.9	4.0	1.9
	from above to 1st bloom on 5th cluster	8.2	4.8	9.1	3.5
	from above until May 1	11.3	6.8	11.3	3.6
	from above until June 1	10.0	5.0	9.1	3.2
	from above until end of crop	5.7	2.9	5.8	2.5

set to engage at 20 °C, but it was later discovered that both heaters in the treatment house were engaging at approximately the same time as expected, but only one heater was engaging in the control. Both heaters were not engaging simultaneously because the thermostats were not set with the required exactness, so one heater would heat the air before the temperature fell to the set point of the second heater. This was corrected during the spring season in late February by forcing a single heater in each house to be primary (engaging at 20 °C) and the second heater as backup (engaging at 17 °C). Since the intake pipes for the air distribution system were on the southern end of the greenhouse, the northern heaters were selected as primary, because warm air was forced toward the southern end. This allowed the warmer air to be discharged through the tubes and into the canopy. The cooling stages were set at 24, 25, 27, and 29 °C (cooling pad). During the first stage, the low speed of the eastern ventilation fan would engage, and the small louver would open. Next, the same ventilation fan would engage to high, and the small louver would close while the large vent would open. The third stage required all ventilation fans to engage and all louvers to open. The last stage required the water pump to engage on the cooling pad, thus reducing the air temperature through the process of water evaporation.

In November and December, the top ventilation fan was manually engaged each morning for about two minutes to remove moisture from the house resulting from nighttime respiration and transpiration. During the spring season, the fan was automated with a timer to engage in early morning and late evening to remove humidity.

Supplemental Air Distribution System

Design Concept

The design goal for the supplemental air distribution system was to provide a simple and inexpensive method to deliver warm air from above the canopy to within the canopy without hindering plant growth or routine greenhouse operations. The design was also required to meet the standard minimum airflow rate for internal air circulation of 15 air exchanges per hour.

Fans were to be used to deliver air through perforated tubes. One fan/duct assembly was to be employed in each double row of tomato plants, with the tube penetrating between the single rows. The volume of a mature canopy in a double row was estimated to be 50 m^3, based on the perpendicular dimensions. This volume was the basis for calculating the required air exchange rate. A minimum airflow rate of 12 m^3/min was required to meet the standard minimum air exchange rate. The air above the canopy was to be piped to the intake of the fan.

Construction and Implementation

The air distribution system was incorporated into the treatment house for each season. Centrifugal fans (Dayton Model 4C445, Dayton Electric Mfg. Co., Niles, IL) were used to inflate perforated ducts, which were constructed from 6-mil polyethylene tubes (BCU Plastics and Packaging, Atlanta, GA). A duct diameter of 16 cm was used because it was the maximum size available that was not expected to be a hindrance for plant growth or routine greenhouse operations. The maximum size was preferred because discharge uniformity along the duct increases with diameter. The size and longitudinal spacing of the perforations and the fan selection were based on the procedures outlined by Amos and Wells (1994) (Appendix A). The selected fan for each tube delivered an airflow of 12 m^3/min at a static pressure of 75 Pa. A hollow hole punch was used to punch 1-cm dia. perforations along the duct at a longitudinal spacing of 26.4 cm, oriented at 11 and 1 o'clock and at 5:30 and 6:30 positions around the circumference of the tube (Figure 3). It was expected that this would provide discharge towards the seedlings in both rows early in the season and provide both upward and downward air movement in a mature dense canopy late in the season. A straight 1.5-m section of steel duct piping attached to the intake of each fan conveyed the air above the canopy to the fan inlet. A fan/tube system was mounted 110-cm high on the first trellis post of each double row of plants on the exhaust side (southern end) of the greenhouse (Figure 4). The exhaust end was chosen to avoid blowing cold air from the inlet louvers directly onto the plants. The perforated duct was supported by a high-tensile wire running along the length of the row. A screen was placed over each intake pipe to avoid loss of bumblebees. The system ran continuously throughout the season (fans rated for continuous operation).

Data Acquisition

A datalogger (Model CR10X, Campbell Scientific, Inc., Logan, UT) wired to two multiplexers (Model AM32, Campbell Scientific, Inc., Logan, UT) was used in each house to record all environmental data. Type T thermocouples (TC) were utilized in each house at five vertical locations: three positions equally spaced along the middle double row and a central location in each of the side rows (Figure 5). At each vertical location, five thermocouples were suspended at 61 cm increments, starting at 61 cm from the ground. An additional TC was installed in the spring season directly at the thermostats for calibration purposes of the thermostat settings. Each TC was shielded from direct

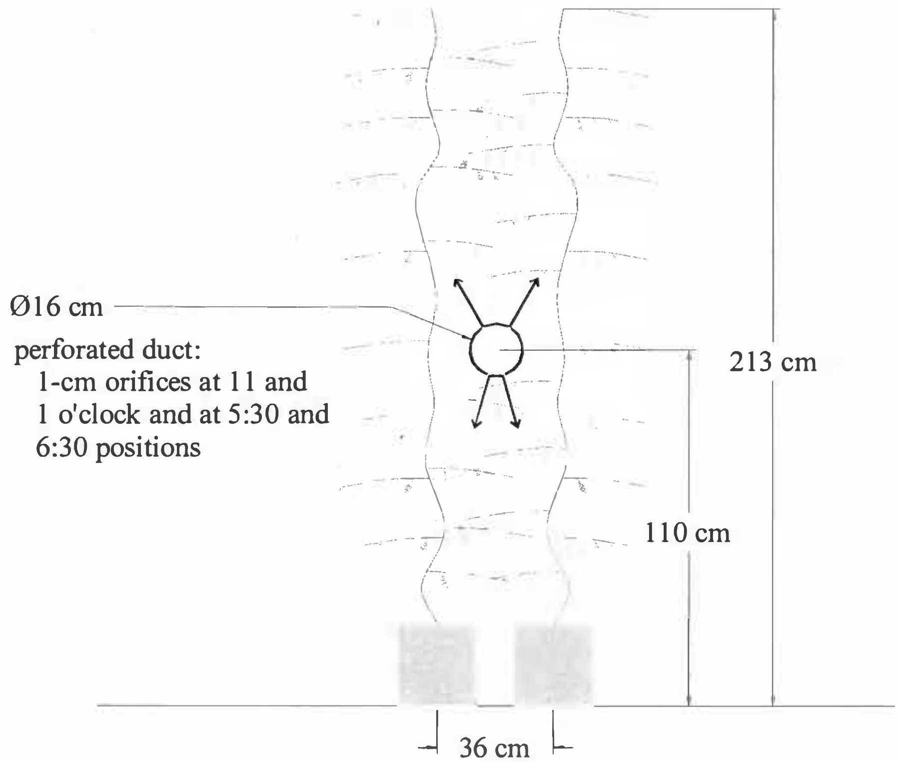


Figure 3. Transverse cross-section of perforated duct inside plant canopy.

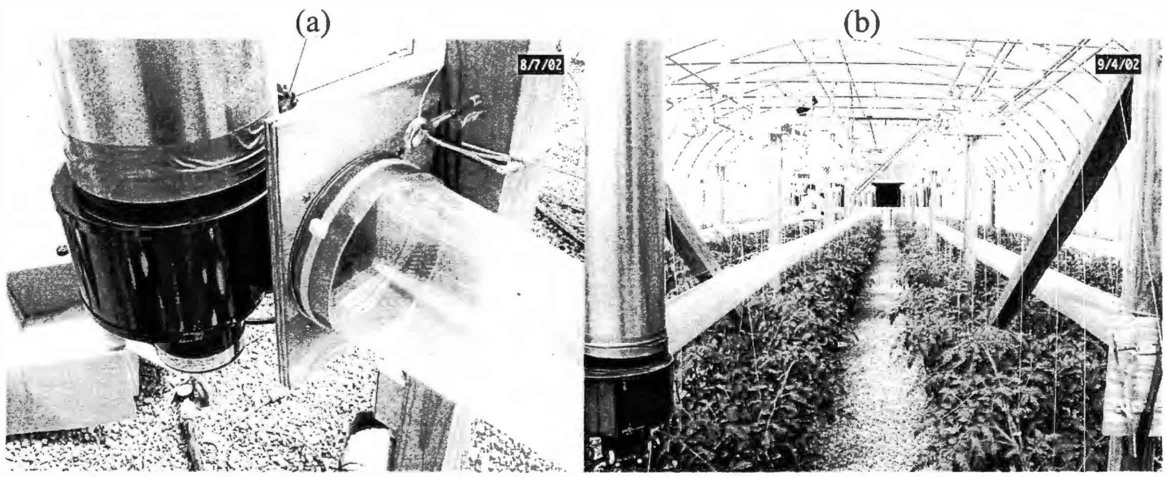


Figure 4. Fan/duct assemble. (a) Fan assembly mounted on trellis post; (b) perforated duct extending length of row.

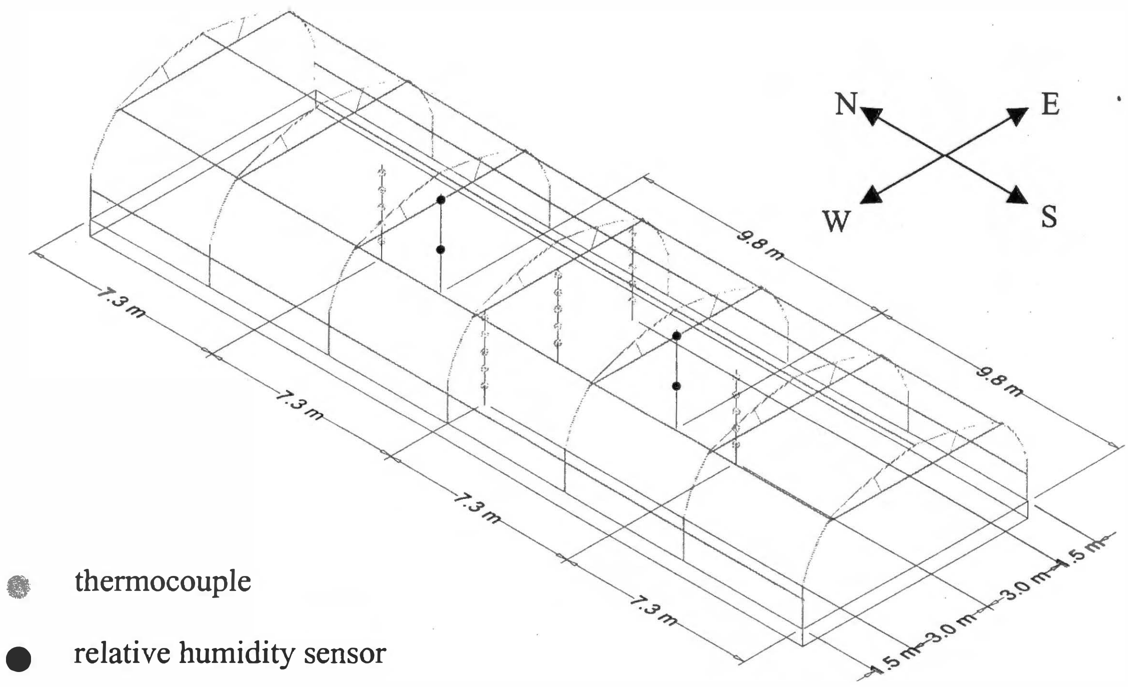


Figure 5. Vertical locations of thermocouples and relative humidity sensors.

sunlight with an expanded polystyrene foam cup to avoid radiant heat gain. Relative humidity/temperature probes (Models HMP35C/45C, Campbell Scientific, Inc., Logan, UT) with solar shields were used at four locations in each house. The vertical locations were at the 1/3rd and 2/3rd positions in the middle double row (Figure 5). At each vertical location, one sensor was fixed above the canopy 3 m from the ground, and one sensor was adjusted during the season to maintain approximately mid-canopy height. Two carbon dioxide sensors (Model GMM222, Vaisala, Woburn, MA) were located near the center of each house. All four carbon dioxide sensors were calibrated against one another before installation, and the hourly mean differences among the sensors were within +/- 8 ppm. Like the humidity sensors, one remained fixed above the canopy, while the other dynamically moved to maintain mid-canopy height. Incoming solar radiation was measured high in the center of each house with a silicon pyranometer (Model LI200X, Campbell Scientific, Inc., Logan, UT). The datalogger was programmed to read all sensors every five minutes and average the measurements over each hour to send to final storage. On a few selected days throughout the spring season, measurements were recorded every minute so the cycling of the heaters could be closely evaluated.

Data Analysis

Environmental Data

The evaluation of the environmental data was separated into nighttime and daytime regimes. Table 3 lists the evaluated periods during the spring growing season. Monthly sunrise and sunset times were identified to the nearest hour using the data from the pyranometers inside the greenhouses. The transitional hour during sunrise and the transitional hour during sunset were removed from the data analysis, so the evaluated

Table 3. Environmental evaluation periods during the spring growing season; times based on Eastern Standard Time (standard time); data for May not available.

	Evaluated Periods	
	Nighttime	**Daytime**
February	7:00 p.m. - 7:00 a.m.	9:00 a.m. - 5:00 p.m.
March	8:00 p.m. - 7:00 a.m.	9:00 a.m. - 6:00 p.m.
April	8:00 p.m. - 6:00 a.m.	8:00 a.m. - 6:00 p.m.
May	N/A	N/A
June	9:00 p.m. - 6:00 a.m.	8:00 a.m. -7:00 p.m.
July	9:00 p.m. - 6:00 a.m.	8:00 a.m. -7:00 p.m.

periods were distinctly dark or light. Monthly averages were calculated for nighttime and daytime based on daily averages through the respective period.

Longitudinal, transverse, and vertical temperature gradients, as well as vertical relative humidity gradients and CO_2 concentrations between the control and treatment houses were evaluated. Environmental gradient differences between houses were statistically analyzed using t-tests with a confidence interval of 95%. Positive gradients were defined as increasing from bottom to top for vertical gradients, north to south for longitudinal gradients, and west to east for transverse gradients. All gradients were interpolated between sensors and never extrapolated beyond the sensors. Table 4 lists the orientation of the evaluated gradients. The interpolated zones for the vertical temperature gradients were labeled as shown in Figure 6. The thermocouple at the 1.2-m height at each vertical location was used for all longitudinal and transverse thermal gradient calculations, representative of mid-canopy (mature) height.

Temperature deviations from both the heating (nighttime) and cooling (daytime) set points were also evaluated. All thermocouples at correlating heights were averaged to obtain the deviation of each level (Level 1 – Level 5). Figure 6 illustrates the level

Table 4. Gradient orientation.

Environmental Factor	Gradient	Label	Interpolated Range	Reference
temperature	vertical	Zone 1	61 – 122 cm	ground
		Zone 2	122 – 183 cm	ground
		Zone 3	183 – 244 cm	ground
		Zone 4	244 – 305 cm	ground
	longitudinal	N – C (North – Center)	7.3 – 14.6 m	northern wall
		C – S (Center – South)	14.6 – 21.9 m	northern wall
	transverse	W – C (North – Center)	1.5 – 4.6 m	western wall
		C – E (Center – South)	4.6 – 7.6m	western wall
relative humidity	vertical	North (9.8 m from northern wall)	0.46 to 1.1* – 2.4 m	ground
		South (19.5 m from northern wall)	0.46 to 1.1* – 2.4 m	ground
	longitudinal	North - South	9.8 – 19.5 m	northern wall

* bottom sensor was raised as the canopy grew to maintain mid-canopy height

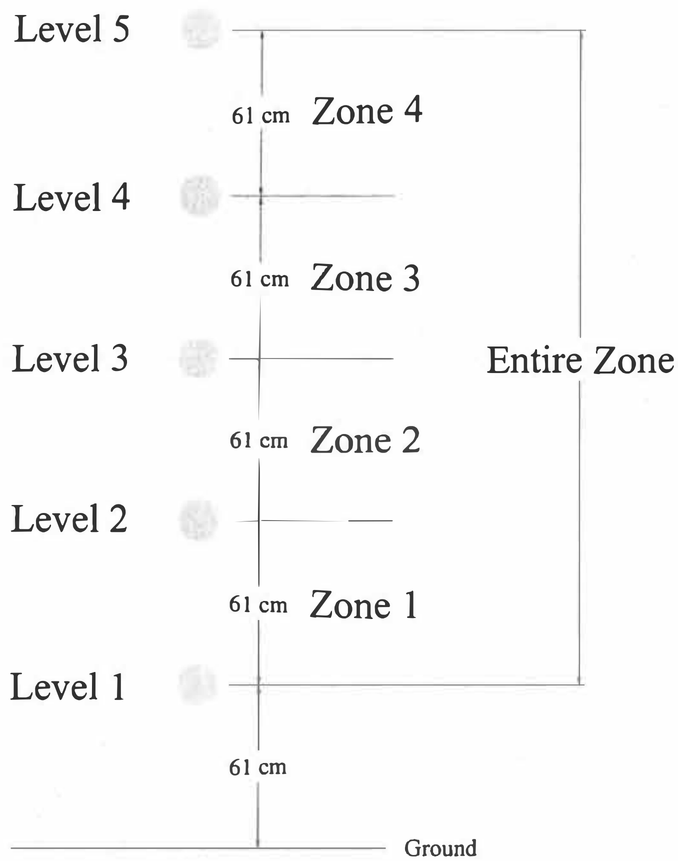


Figure 6. Labeling scheme for vertically oriented thermocouples; zones refer to distance between thermocouples while levels indicate exact height.

nomenclature with respect to the vertical zones. Each thermocouple at the 1.2 m height was also independently evaluated, so the temperature deviations in all directions were analyzed. Humidity and carbon dioxide levels were also assessed.

Yield Data

Harvested marketable tomatoes were graded in four size categories and weighed. Yield from each double row was recorded separately.

Fuel and Electricity

Fuel consumption and electricity usage were recorded for each house during both test periods.

Chapter 3 – Results and Discussion

Fall Results

The fall season was considered a trial run. Defects in the structure and equipment in the newly constructed greenhouses were identified and repaired. Also, experimental operational details were refined. Furthermore, yields from the fall crop were low as was the case for most greenhouse tomato producers in Tennessee due to unseasonably cool and wet weather conditions (Straw, 2003, Pers. Comm.). For these reasons, the environmental and yield results were highly questionable and will only be referred to in context of the spring results.

Spring Results

Environmental Conditions in Greenhouses

Environmental data for May is not available due to datalogger failure.

Vertical Gradients – Nighttime

The nighttime vertical temperature gradients through Zones 1 (61 – 122 cm) and 2 (122 – 183 cm) were significantly lower in the treatment house than in the control in February, March, and April ($P = 0.05$), while the differences through Zones 3 (183 – 244 cm) and 4 (244 – 305 cm) were less significant. The nighttime vertical temperature gradients are shown in Table B1. Positive gradients are defined as increasing from bottom to top. Figure 7 illustrates this trend during February and March. The most severe vertical temperature stratifications during the nighttime occurred during February, with the treatment and control houses averaging 1.0 and 1.8 °C/m through the entire vertical range, respectively. These gradient values resulted in temperature differences of 2.3 °C in

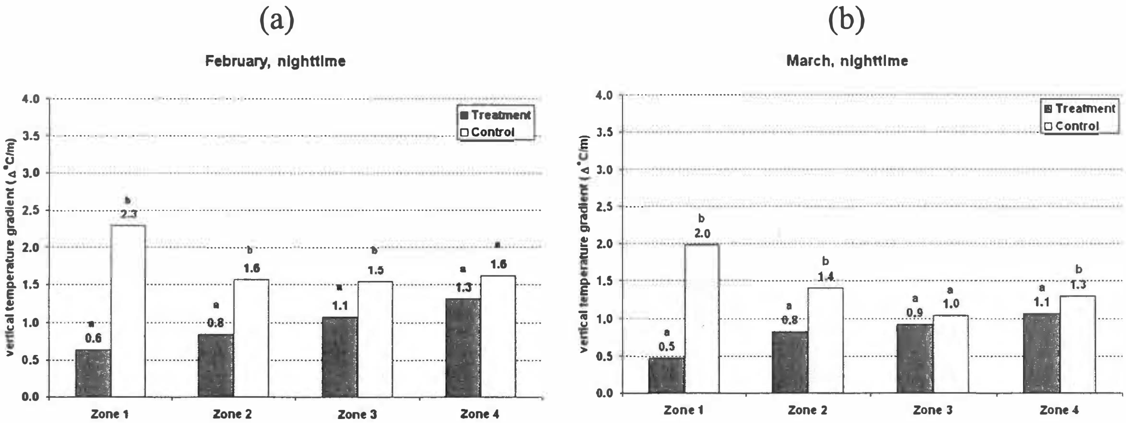


Figure 7. Nighttime vertical temperature gradients. February (a) and March (b); letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone or at each level, with 'b' being significantly different from 'a' (P = 0.05).

the treatment house and 4.3 °C in the control house over the entire vertical range. Nighttime vertical temperature gradients were negligible in June (Figure 8) and July.

Monthly nighttime temperature deviations from the heater set point (20 °C) at each vertical level are given in Table B2. The monthly temperature deviations between the houses were significantly different at Level 1 (61 cm) from February through April (P = 0.05), with the treatment house consistently warmer. The largest difference occurred in February when the treatment house was 1.6 °C warmer than the control house at the bottom level. The temperatures in the treatment house at Level 1 were kept above the heater set point, while the temperatures in the control house at the same level fell below the set point during February and March. However, the temperatures at Levels 4 (244 cm) and 5 (305 cm) were consistently cooler in the treatment house than the control house from February through April. This trend is illustrated in Figure 9, which shows the deviations from the heater set point at all levels for each house during February and March. No significant differences occurred between houses in the nighttime temperature

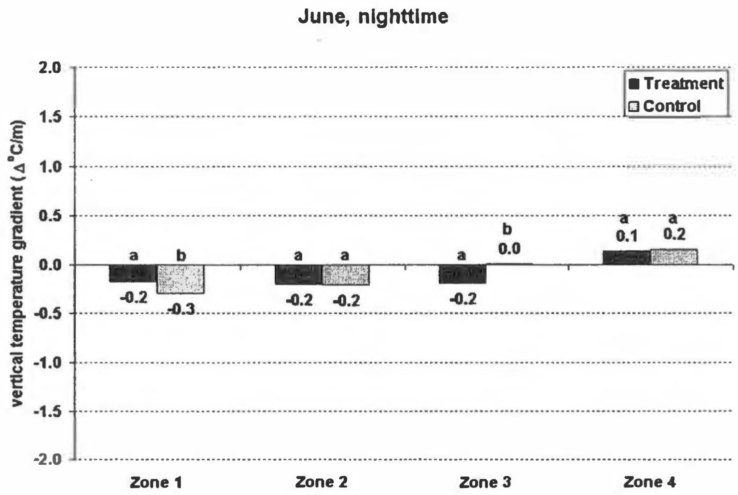


Figure 8. Nighttime vertical temperature gradients during June; letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

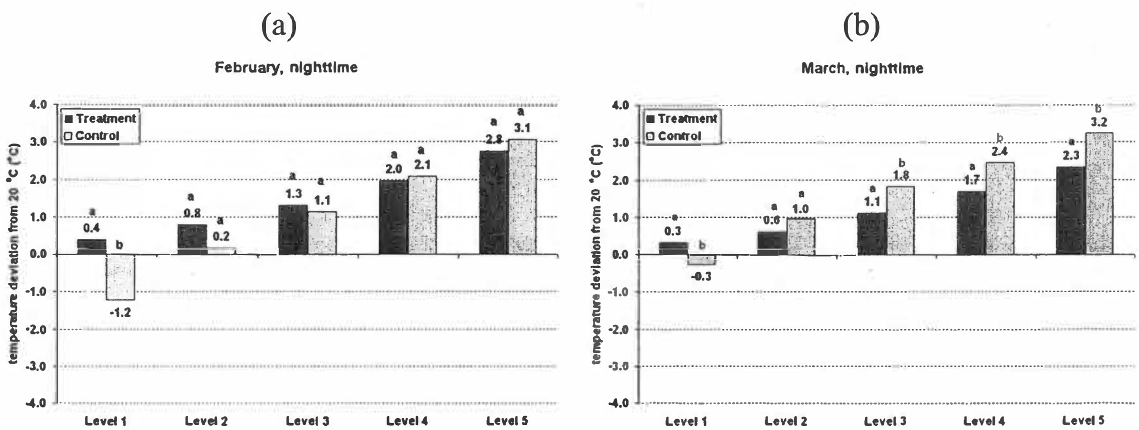


Figure 9. Nighttime temperature deviation from heating set point (20 °C). February (a) and March (b); letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone or at each level, with 'b' being significantly different from 'a' (P = 0.05).

deviations during June or July (P = 0.05), though the treatment house was consistently 0.5 to 0.8 °C warmer at all levels.

Monthly nighttime vertical relative humidity gradients are presented in Table B3. Positive gradients were defined as increasing from bottom to top. Nighttime vertical relative humidity gradients at both the northern and southern ends were significantly reduced in the treatment house from February through April (P = 0.05), with the greatest differences occurring in the first two months (Figure 10). The treatment house experienced significantly higher gradients during June and July because the humidity sensors in the control house were closer to 100% rh at both the bottom and top sensor locations.

The monthly nighttime relative humidity values at each sensor location are given in Table B4. The relative humidity within the canopy on the northern end ranged from 95 to 100% in the control house from March through July, while the treatment house ranged

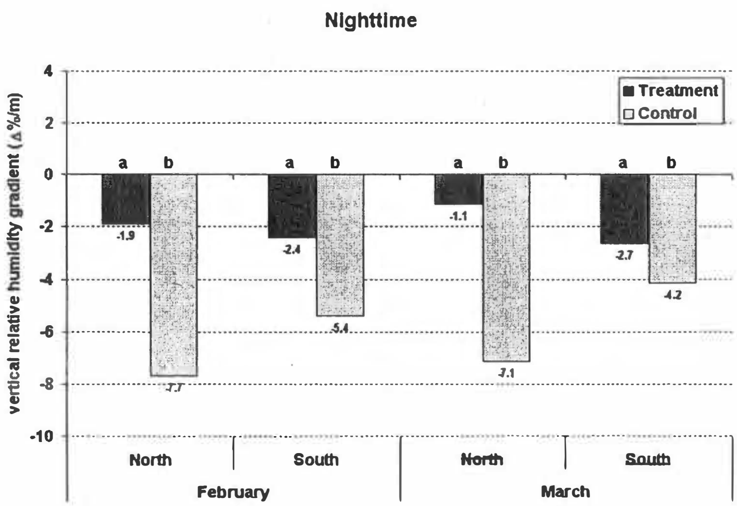


Figure 10. Nighttime vertical relative humidity gradients for each house during February and March at the northern and southern ends; letters 'a' and 'b' indicate significant differences between treatment and control houses at each sensor location, with 'b' being significantly different from 'a' (P = 0.05).

from 91 to 97% (Figure 11). The differences between the houses were significant for each of those months (P = 0.05).

Nighttime vertical carbon dioxide gradients were also evaluated and presented in Table B5. Positive gradients were defined as increasing from bottom to top. The monthly gradients were significantly different between houses for the entire season. Also, all monthly gradient values for the treatment house were positive, while all were negative in the control house (Figure 12). There was little change in the gradient values from month to month within each house. The average nighttime gradients over the growing season were 14 and -23 ppm per meter in the treatment and control houses, respectively.

The nighttime carbon dioxide concentrations for each house are shown in Table B6. Concentrations were consistently higher in the treatment house within and above the canopy throughout the entire growing season (Figure 13a,b). Averages ranged

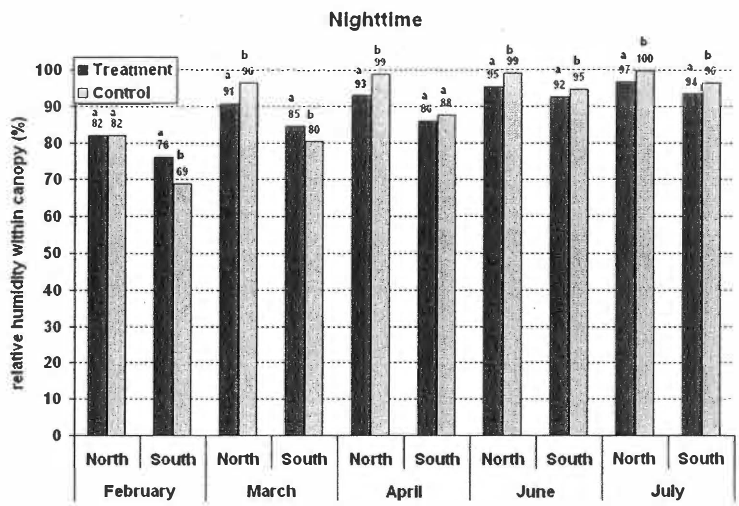


Figure 11. Nighttime relative humidity within the canopy; letters 'a' and 'b' indicate significant differences between treatment and control houses at each location, with 'b' being significantly different from 'a' (P = 0.05).

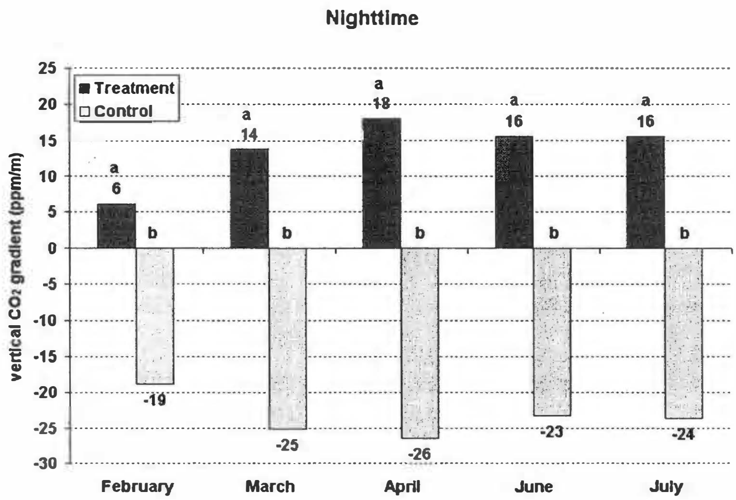
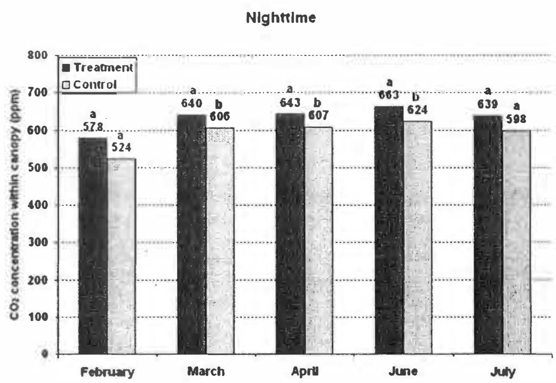


Figure 12. Nighttime vertical carbon dioxide gradients; letters 'a' and 'b' indicate significant differences between treatment and control houses through each zone, with 'b' being significantly different from 'a' (P = 0.05).

(a)



(b)

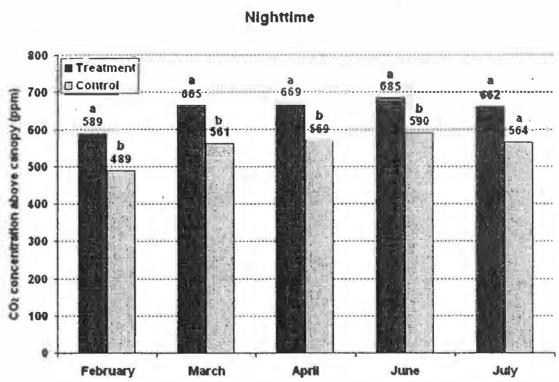


Figure 13. Nighttime CO_2 concentrations. Within (a) and above (b) the canopy; letters 'a' and 'b' indicate significant differences between treatment and control houses during each month, with 'b' being significantly different from 'a' (P = 0.05).

from 578 to 685 ppm and from 489 to 624 ppm in the treatment and control houses, respectively.

The supplemental air distribution system proved to be most effective in reducing nighttime vertical temperature gradients during periods when supplemental heat was required, primarily during February and March (Figure 7). The gradients were reduced because the air distribution system removed heated air above the plant canopy and distributed it to lower levels within the canopy. Figure 9 illustrates this concept during these months by showing that the temperatures at Levels 4 (183 cm) and 5 (305 cm) were cooler in the treatment house but warmer at Level 1 (61 cm) where the bulk of the canopy existed at that time. The substantially higher gradients in the control house during February indicated that vertical temperature stratifications occurred through open air space when the canopy mass was small (Figure 7a). However, the same trend occurred during March as the canopy grew taller (Figure 7b). This similarity suggests that the canopy does not have a considerable effect on nighttime vertical temperature gradients during heating modes. Negligible gradients occurred in both greenhouses in the warmer months when no supplemental heating was required (Figure 8), indicating no benefit of the air distribution system during this period.

The system was also effective in reducing vertical relative humidity gradients during the nighttime in February through April, with the most obvious effects during the first two months (Figure 10). Humidity ratios (kg of moisture per kg of dry air) were calculated for the monthly nighttime periods at each sensor location to determine if the relative humidity gradients primarily resulted from absolute moisture gradients or from temperature gradients. Humidity ratios throughout the season at each sensor location within the canopy are presented in Figure 14a and above the canopy in Figure 14b. The maximum difference from within the canopy to above the canopy of all locations in both houses was 0.0016, which was only an increase of 7% inside the canopy compared to above the canopy. The average differences in humidity ratios from below to above were 0.0003 (s. d. = 0.009) and 0.0002 (s. d. = 0.006) in the treatment and control houses, respectively. Since the differences were negligible, then the relative humidity gradients were primarily caused by the temperature gradients, not differences in humidity ratios. Figure 14 also shows an increase in the total quantity of moisture in the treatment house compared to the control house within and above the canopy. The most extreme difference in the nighttime humidity ratios based on an averaged value from all four sensor locations occurred during February, with the treatment house experiencing 22% more moisture in the air than the control house. A potential reason may be because the increased air movement coupled with the slightly higher temperatures increased nighttime respiration and/or transpiration rates.

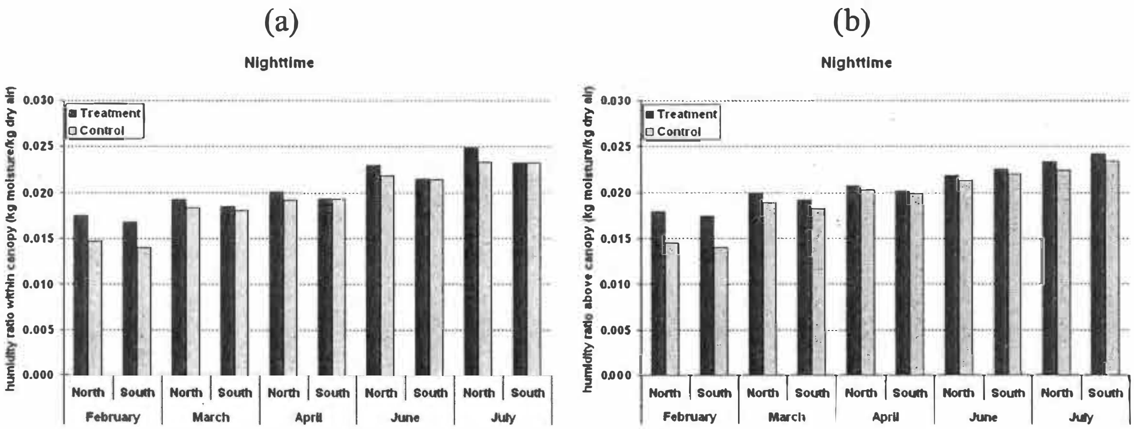


Figure 14. Nighttime humidity ratios. Within (a) and above (b) the canopy.

The air distribution system was suspected to be the cause of the reversed vertical carbon dioxide gradients between the greenhouses during the nighttime (Figure 12). In the control house, the higher concentrations were found to be in the canopy, while in the treatment house they occurred above the canopy (Figure 13). However, concentrations were higher in the treatment house, than the control house at all locations throughout the season. It is hypothesized that more condensation occurred on the foliage in the control house, which reduced nighttime respiration rates. The increased air movement in the treatment house may have also reduced the boundary layer at the leaf surfaces, allowing more oxygen to become available for respiration. It is probable that the higher nighttime respiration rate in the treatment house slightly reduced the canopy biomass, though no measurements were taken.

The environmental differences between the greenhouses throughout the season resulted in a yield increase of 14% in favor of the treatment house. The average fruit sizes were 182 and 184 g/fruit in the treatment and control houses, respectively, but were not significantly different ($P = 0.05$). From the evaluation of the nighttime vertical gradients, it was suspected that the decreased relative humidity levels in the treatment house within the canopy had the greatest impact on the increased production. However, the relative humidity was primarily influenced by temperature, as previously explained. The general trend of production increasing with decreasing nighttime relative humidity levels was in agreement with Bakker (1990), who indicated an 8% yield increase in a beefsteak tomato variety when the average nighttime relative humidity was 72% (18.7 °C) compared to 88% (17.9 °C). The control house experienced consecutive nighttime hours at 100% rh at the northern end, causing a high degree of moisture to condense on the leaf surfaces. It is hypothesized that the condensation decreased the available oxygen for respiration, as well as inhibited nighttime transpiration. Prolonged saturated conditions also promote disease infestation, such as gray mold. However, no disease occurrences appeared in either house during the spring season.

The direct physiological effects of the nighttime temperature differences were suspected to have negligible effects on the cumulative yield, based on the evaluation of the averaged vertical levels. The temperatures never fell to a yield-threatening value at any of the levels in either greenhouse. The maximum monthly nighttime difference between all corresponding vertical levels within each house occurred at Level 1 during February, with the treatment house 1.6 °C warmer than the control house (Figure 9a). The largest difference from March through July among levels within the canopy was only 0.8 °C, occurring in July. The effects of the nighttime temperature differences were considered minor with regards to the final yield.

Vertical Gradients - Daytime

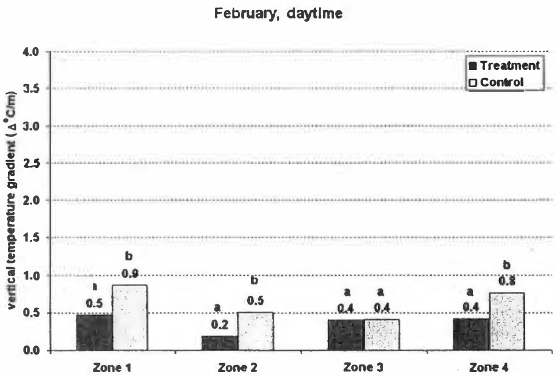
Daytime vertical temperature gradients are presented in Table B7. Positive values were defined as increasing from bottom to top. The vertical temperature gradients at Zones 1, 2, and 4 were significantly reduced in the treatment house during February ($P = 0.05$), with the greatest values of 0.87 and 0.48 °C/m at Zone 1 in the control and treatment houses, respectively (Figure 15a). The temperature ranges across the entire vertical zones during that period in the control and treatment houses were 1.6 and 0.9 °C, respectively. During March, both greenhouses experienced considerably higher daytime gradients through Zone 1 than the upper zones, but the gradients were not significantly different between the greenhouses at Zone 1 (Figure 15b). The temperature range across Zone 1 during March was 1.2 and 1.1 °C in the treatment and control house, respectively. Considerable gradients also occurred in both greenhouses during April in Zones 1 and 2 (Figure 15c) and during June (Figure 15d) and July in Zones 2 and 3. The temperature ranges through these individual zones were from 0.5 to 1.9 °C.

Daytime temperature deviations from the low-stage ventilation set point (24 °C) for each vertical increment are shown in Table B8. No significant differences in the daytime deviations between greenhouses were found throughout the entire season, with an exception of Level 3 in June ($P = 0.05$). The temperatures were maintained between the heating and cooling set points in both greenhouses during February and March. However, the average monthly daytime values in each house exceeded the ventilation set point at all levels in June and July and Levels 3 through 5 in April.

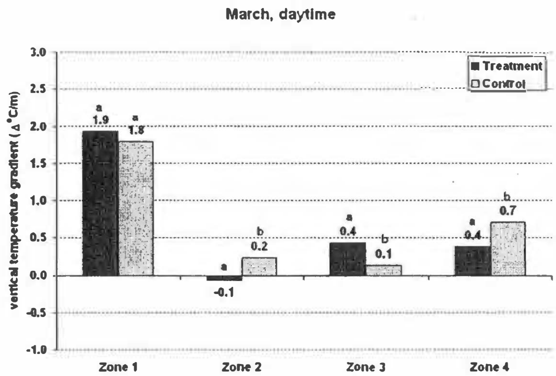
Vertical relative humidity gradients for the daytime are listed in Table B9. Positive gradients were defined as increasing from bottom to top. The daytime gradients in the control house were significantly more severe during February, March, June, and July (Figure 16). The largest gradient in the treatment house occurred during April on the southern end, which resulted in a decrease of 4.5% rh from bottom to top. The control house experienced its largest gradient in June on the southern side, resulting in a decrease of 5.9% rh from bottom to top.

Daytime relative humidity values at each sensor location are shown in Table B10. No significant differences in daytime relative humidity occurred between houses throughout the entire season ($P = 0.05$). The daytime monthly relative humidity never

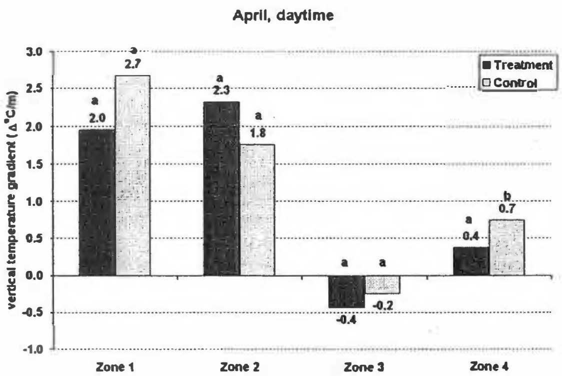
(a)



(b)



(c)



(d)

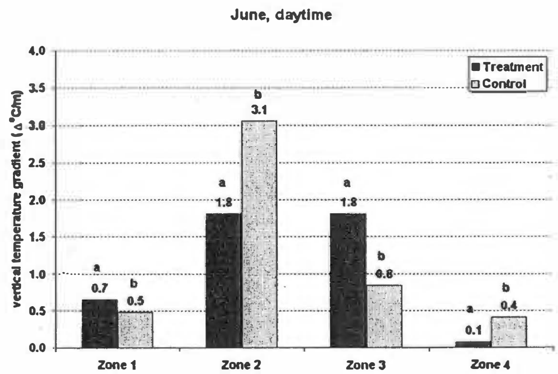


Figure 15. Daytime vertical temperature gradients during (a) February, (b) March, (c) April, and (d) June; letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

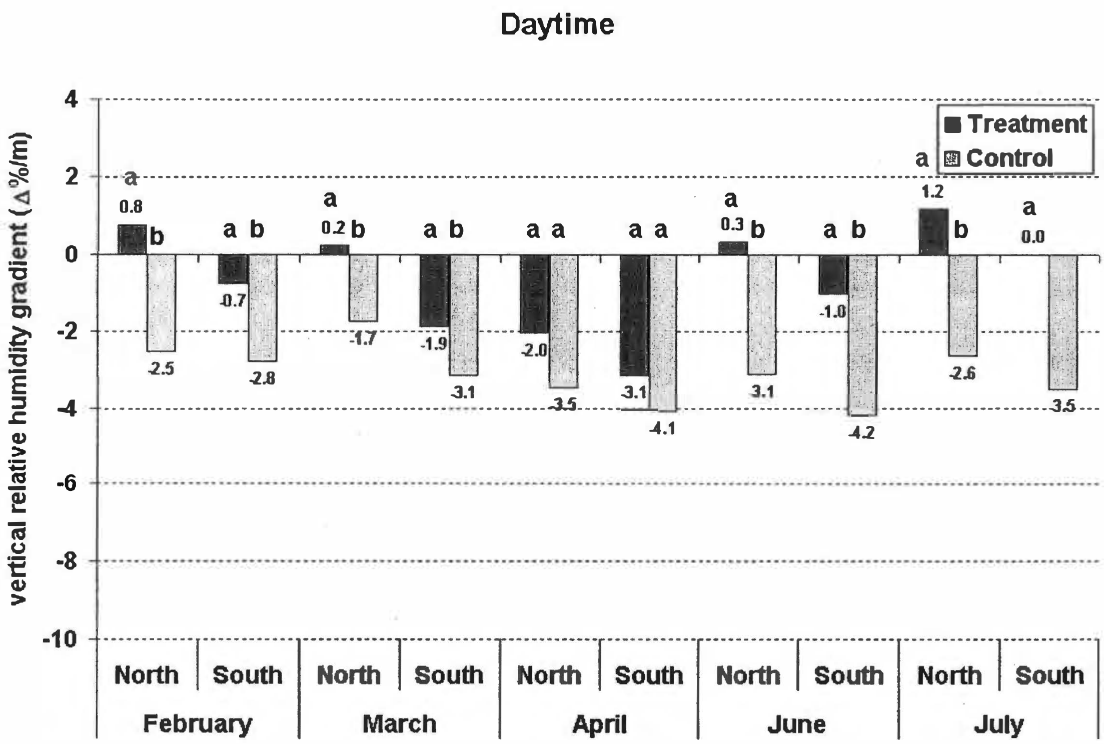


Figure 16. Daytime vertical relative humidity gradients at the northern and southern ends; letters 'a' and 'b' indicate significant differences between treatment and control houses at each sensor location, with 'b' being significantly different from 'a' (P = 0.05).

exceeded 83% in either greenhouse from February through June. Values during July reached near 94% in both greenhouses.

Daytime vertical carbon dioxide gradients are reported in Table B11. Positive values were defined as increasing from bottom to top. The daytime gradients were significantly more severe in the control house than the treatment throughout the season. The gradients were primarily negative, indicating that concentrations decreased from bottom to top. The most severe changes through the vertical zone occurred during June and July, with concentrations decreasing by 20 and 40 ppm in the treatment and control houses, respectively.

Daytime carbon dioxide concentrations are given in Table B12. No significant differences in daytime concentrations between the greenhouses were found within the canopy (Figure 17a). However, the concentrations above the canopy were significantly higher in the treatment house in March, April, and June (Figure 17b). The averages above the canopy during March, April, and June were 383 and 357 ppm in the treatment and control houses, respectively.

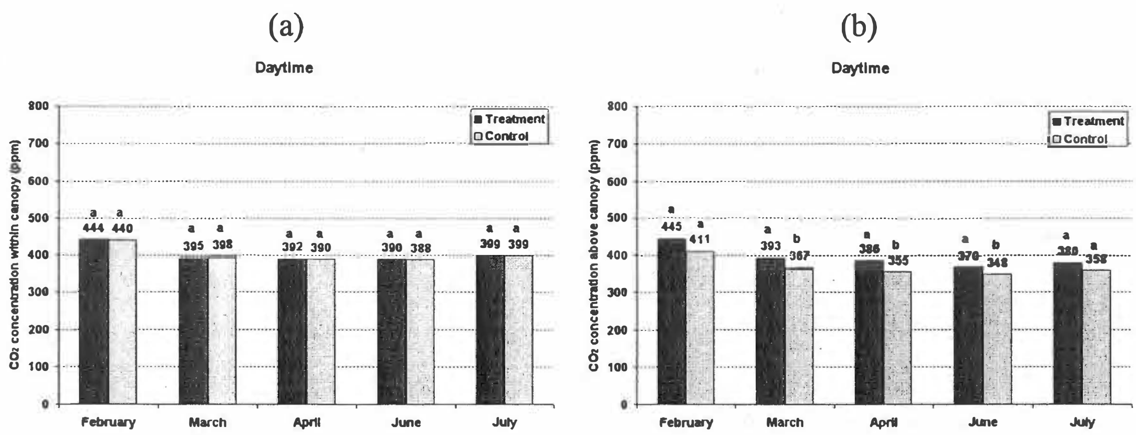


Figure 17. Daytime CO_2 concentrations. Within (a) and above (b) the canopy; letters 'a' and 'b' indicate significant differences between treatment and control houses during each month, with 'b' being significantly different from 'a' (P = 0.05).

The effectiveness of the supplemental air distribution system on vertical temperature gradients was not as substantial during the daytime as was the nighttime because less supplemental heating was required during daylight hours. Some supplemental heating was required during February, a slight amount in March, and none in April through July. The differences between daytime and nighttime vertical temperature gradients during February can be observed by comparing Figures 9a and 15a. The daytime gradients in both greenhouses through the entire vertical zone during February are approximately one third of the nighttime gradients. Though the daytime gradients were less considerable than the nighttime through that period, the air distribution system significantly reduced the temperature stratification in Zones 1, 2, and 4 by forcing the heated air towards the lower levels. During the warmer months when cooling was required, the air movement caused by the supplemental air distribution system was considered negligible compared to the air movement induced by the ventilation fans.

As the season progressed, the effectiveness of the air distribution system diminished in regards to temperature. Substantial gradients occurred in both houses beginning in March and lasting till the end of the season. The primary source of the gradients was suspected to be shading within the canopy. As the canopy engulfed Zone 1 during March, both houses experienced considerably higher daytime gradients through that zone than the upper zones (Figure 15b). The plants grew to surpass Zone 2 in April, and much larger gradients were observed in Zones 1 and 2 (Figure 15c). The gradients in the mature canopy during June can be observed in Figure 15d. The maximum canopy height extended near the middle of Zone 3, and substantial gradients occurred in Zones 2 and 3 during June and July. The gradients through Zone 1 during this period were low probably because most of the lower limbs were pruned, and the existing lower limbs were withered, nearly leaving Zone 1 free of foliage. Daytime gradients occurring through zones of open air space were generally low through the entire season.

The air distribution system had some effect in reducing the vertical relative humidity gradients during the daytime periods of February resulting from the temperature effects, but the relative humidity levels were not considered a physiological threat in either house throughout the season. However, it is likely that the additional air movement induced by the system increased daytime transpiration rates during the cooler months, when daytime cooling was not required. The treatment house experienced a 17% higher humidity ratio during the daytime than the control, averaged over the four sensing locations (Figure 18). As the season progressed, the differences were considerably reduced because the air in the greenhouses was being constantly exchanged with outside air by the ventilation system.

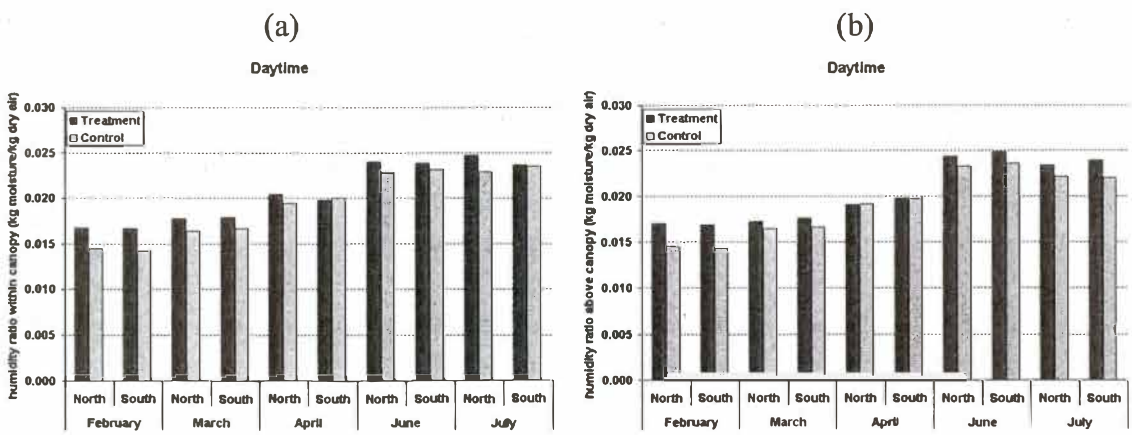


Figure 18. Daytime humidity ratios. Within (a) and above (b) the canopy.

No significant differences in carbon dioxide concentrations occurred within the canopy between the greenhouses throughout the entire season. Therefore, the air distribution system offers no benefit in regards to carbon dioxide availability to the plants.

It is probable that the additional air movement during the daytime of the cooler months had some effect on the overall yield difference between the greenhouses. It is hypothesized that the rate of fruit production increased due to the suspected increase in the daytime transpiration rate, which increased water and nutrient uptake. The environmental differences between the greenhouses during periods of heavy ventilation in the warmer months were considered negligible.

Longitudinal Gradients – Nighttime

Nighttime longitudinal temperature gradients are reported in Table B13. The gradients were evaluated based on measurements recorded at Level 2 (mid-canopy height), with positive values defined as increasing from North to South. The nighttime longitudinal gradients from the center to southern end were significantly reduced in the treatment house in February and March (Figure 19a), with the treatment and control houses experiencing values as high as 0.1 and 0.2 °C/m, respectively ($P = 0.05$). Values from northern end to the center during this period were negligible in both greenhouses. The longitudinal temperature gradients diminished in June and July (Figure 19b) in both greenhouses.

Nighttime temperature deviations from the heating set point (20 °C) at all Level 2 thermocouples are presented in Table B14. The monthly nighttime temperatures in the

(a) (b)

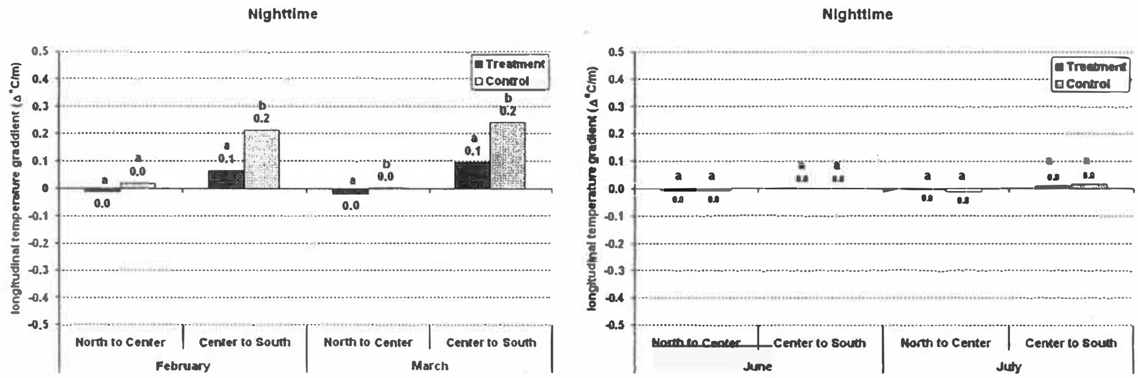


Figure 19. Nighttime longitudinal temperature gradients. February and March (a), and June and July (b); letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

treatment house remained above the heating set point throughout the entire season, while the control house experienced temperatures below the set point at the center and northern end during February (Figure 20). This figure also illustrates that the southern end of the treatment house was cooler, while the northern end was warmer than the control house during February and March. The treatment house was consistently warmer than the control house by more than 0.6 °C at all Level 2 sensors during June and July, though the differences were not significant (P = 0.05).

Longitudinal relative humidity gradients that occurred during the nighttime are reported in Table B15. Positive values were defined as increasing from North to South. All value were negative throughout the season during the nighttime in both greenhouses, indicating that the northern end experienced higher levels of relative humidity. The gradients were significantly reduced in the treatment house from February through June

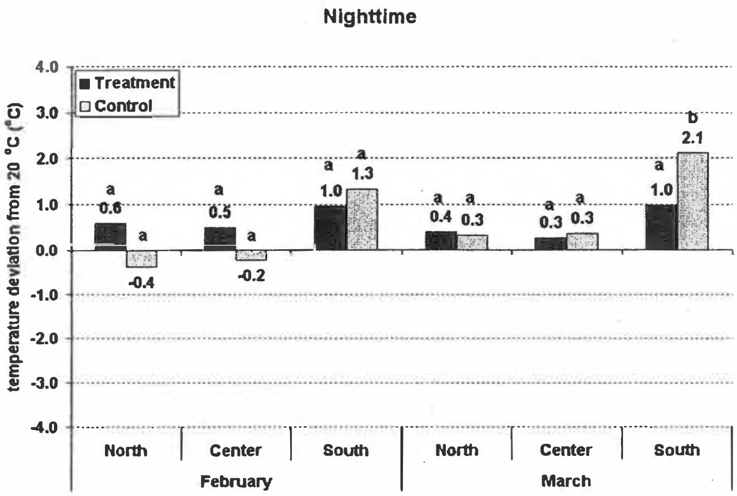


Figure 20. Nighttime temperature deviations from the heating set point (20 °C) from the Level 2 thermocouples at the northern, central, and southern locations; letters 'a' and 'b' indicate significant differences between treatment and control houses at each sensor location, with 'b' being significantly different from 'a' (P = 0.05).

(P = 0.05), with the larger gradients in both greenhouses occurring in the first half of the season (Figure 21). The maximum change in relative humidity measured in the treatment house across the evaluated zone (9.8 m) was 7% occurring in April, and the maximum change in the control house was 16% occurring in March.

The supplemental air distribution system proved to be most effective in reducing nighttime longitudinal temperature gradients during heating modes, as in the vertical gradient analysis. However, the changes in temperatures through the entire longitudinal zones (14.6 m) in both houses were primarily less than the temperature changes through the entire vertical zones (2.4 m) during the nighttime. The longitudinal gradients during the nighttime were caused by the primary heater at the northwestern corner expelling heated air directly toward the southern end, causing the southern side to become warmer than the northern side. The fan intakes for the air distribution system were located on the

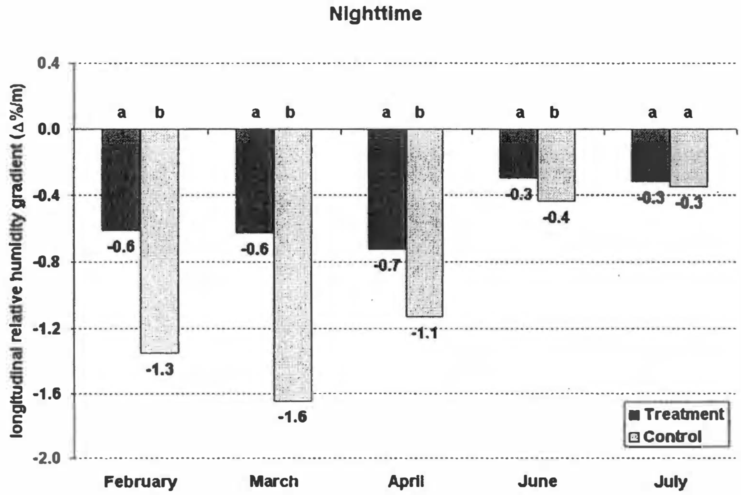


Figure 21. Nighttime longitudinal relative humidity gradients; letters 'a' and 'b' indicate significant differences between treatment and control houses during each month, with 'b' being significantly different from 'a' (P = 0.05).

southern end, so the heated air was diverted directly back towards the northern end through the canopy in the treatment house. A great deal of supplemental heating was required during the nighttime in February and March, and Figure 20 illustrates how the air distribution system reduced the temperature at the southern end, while increasing the temperature at the northern end. During nighttime periods when supplemental heat was not needed, the longitudinal temperature gradients became negligible (Figure 19b).

Like the vertical relative humidity gradients, the nighttime longitudinal gradients were found to be primarily influenced by temperature and not variations in the absolute air moisture. The relative humidity was higher at the northern end of the greenhouses because the temperatures were generally cooler. Therefore, the nighttime effect of the supplemental air distribution system on relative humidity gradients paralleled the effect on the nighttime longitudinal temperature gradients.

The evaluation of the nighttime longitudinal gradients was in agreement with the analysis of the nighttime vertical gradients regarding the effects on cumulative production. The higher yield in the treatment house was suspected to be attributed to the lower relative humidity values compared to the control house, especially at the northern end. The majority of the difference in production between houses probably occurred towards the northern end of the greenhouses, though yield was not recorded in longitudinal increments. The treatment house averaged 93% rh inside the canopy at the northern end from March through June (May excluded from analysis), while the control house averaged 98% rh through that period (Figure 11).

The nighttime temperature differences between greenhouses at correlating Level 2 thermocouples at the northern, central, and southern locations rarely exceeded 1 °C. Therefore, the differences in physiological effects resulting directly from the temperature differences were considered negligible.

Longitudinal Gradients – Daytime

Daytime longitudinal temperature gradients are presented in Table B16. The gradients were evaluated based on measurements recorded at Level 2 (mid-canopy height), with positive values defined as increasing from North to South. The highest gradients occurred during February and March (Figure 22), reaching 0.1 and 0.2 °C/m in the treatment and control houses, respectively, but were not significantly different ($P = 0.05$). The zone from center to southern end constituted for the bulk of the temperature differences within the entire zone. Gradients from April through the end of the season did not exceed 0.1 °C/m in either greenhouse.

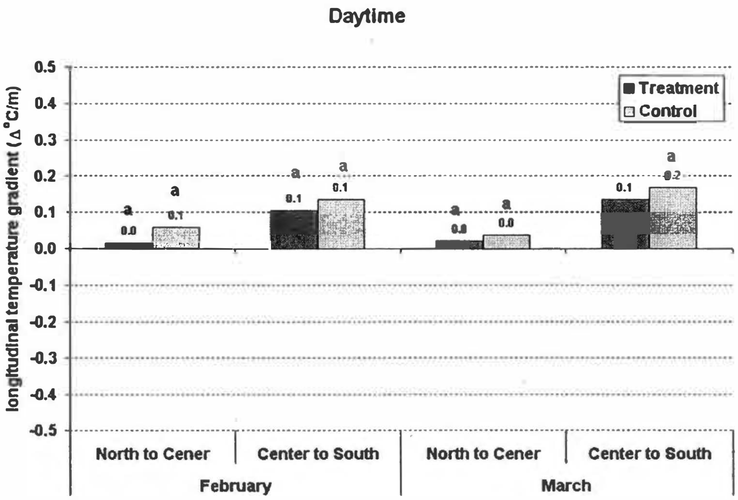


Figure 22. Daytime longitudinal temperature gradients during February and March; letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

Daytime temperature deviations from the low stage ventilation set point (24 °C) measured at the Level 2 thermocouple at the northern, central, and southern locations are listed in Table B17. The monthly temperatures at mid-canopy did not exceed the ventilation set point until June and July (May excluded from analysis). Significantly higher temperatures occurred in the control house than the treatment house at all three locations in April and June (Figure 23), resulting in an average difference of 1 °C during that period.

Longitudinal relative humidity gradients during the daytime are shown in Table B18, with positive values defined as increasing from North to South. The largest gradients in both greenhouses occurred during February, with the treatment house significantly lower (P = 0.05). Those gradients resulted in a decrease of 4 and 8% rh across the evaluated zone (9.8 m) in the treatment and control houses, respectively. The

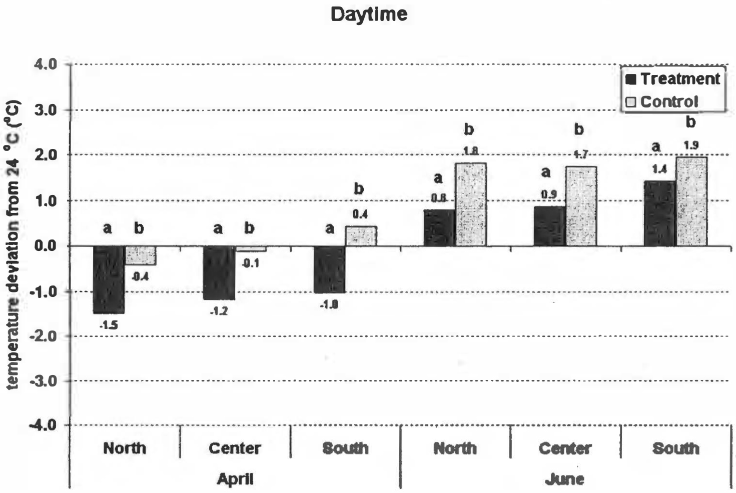


Figure 23. Daytime temperature deviation from the ventilation set point (24 °C) during April and June; letters 'a' and 'b' indicate significant differences between treatment and control houses at each sensor location, with 'b' being significantly different from 'a' (P = 0.05).

daytime longitudinal gradient values from March through July were approximately half or less than values in February.

The effects of the supplemental air distribution system on daytime longitudinal temperature gradients were considered negligible, since no stratifications were substantially reduced.

Also, no benefits were attributed to the air distribution system in terms of longitudinal relative humidity gradients occurring during daylight hours. The relative humidity values in either greenhouse were not at physiologically dangerous levels throughout the season.

The only new finding in the evaluation of the longitudinal gradients that would affect the yield difference between the greenhouses was the increased temperatures occurring in the control house in the latter portion of the season. However, the effect was considered minimal since the temperature differences were only about 1 °C.

The increased temperatures found in the control house at the Level 2 thermocouples at the northern, central, and southern locations was determined to be a solar effect and is further discussed in the daytime transverse analysis.

Transverse Gradients – Nighttime

Nighttime transverse temperature gradients are reported in Table B19. Gradients were determined from the Level 2 thermocouples at the western, central, and eastern locations, with positive values defined as increasing from West to East. The largest gradients occurred during February and March (Figure 24). The treatment house experienced a significantly higher gradient from the western to the central location during February, with a value approximately double of that in the control house. The direction of

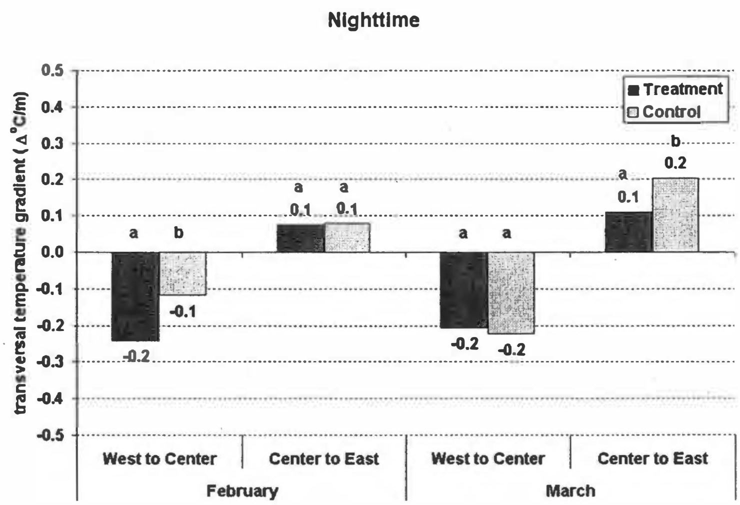


Figure 24. Nighttime transverse temperature gradients during February and March; letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

the gradients indicated that the center row was cooler than the outer rows.

Nighttime temperature deviations from the heater set point (20 °C) at the Level 2 thermocouples are listed in Table B14. The only significant difference between the greenhouses at the corresponding transverse locations occurred during June on the eastern side, with the treatment house 0.8 °C warmer than the control house.

The supplemental air distribution system attributed to the increased transverse gradient from the western side to the central location during February. The intake for the fan/duct assembly on the western row was directly in the path of the air expelled by the heater. Therefore, the warmest air was immediately forced through the western row, causing it to become warmer than the others. No other transverse effects were found to be caused by the air distribution system.

No effects were revealed in the nighttime transverse analysis that could have potentially affected the difference in cumulative yield between the greenhouses.

Transverse Gradients – Daytime

Daytime transverse temperature gradients are given in Table B20. The gradients through both evaluated zones in the treatment house were significantly greater than the control house in April, June, and July (Figure 25). Gradients in the treatment house during February and March were less severe.

Table B17 includes temperature deviations from the ventilation set point (24 °C) at the western, central, and eastern locations at Level 2. Figure 26 illustrates the magnitude of the temperature differences between greenhouses at each location. The outer rows in the treatment house were 0.7 – 1.4 °C higher than the center row in April,

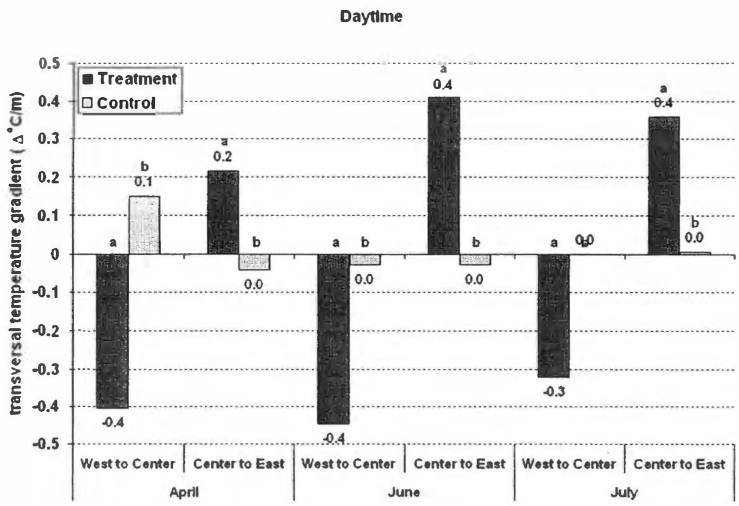


Figure 25. Daytime transverse temperature gradients in April, June, and July; letters 'a' and 'b' indicate significant differences between treatment and control houses within each zone, with 'b' being significantly different from 'a' (P = 0.05).

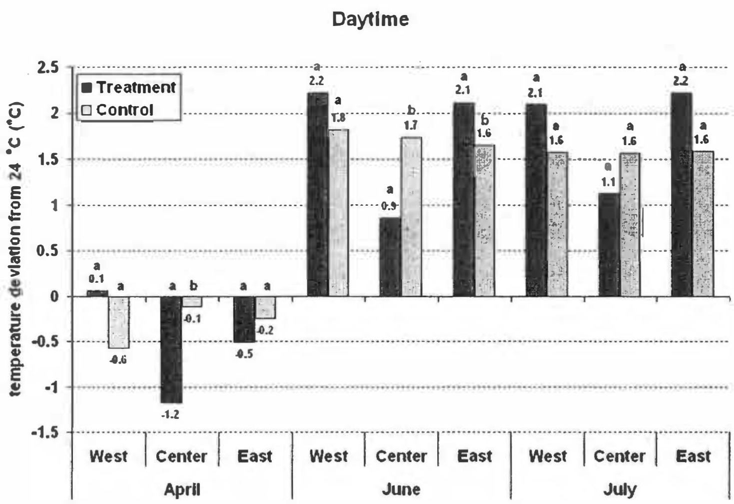


Figure 26. Daytime temperature deviations from the ventilation set point (24 °C) during April, June, and July; letters 'a' and 'b' indicate significant differences between treatment and control houses at each sensor location, with 'b' being significantly different from 'a' (P = 0.05).

June, and July. The control house experienced negligible differences between the outer rows and the center row through the same period.

The differences between the greenhouses in the daytime transverse temperature gradients and deviations were not induced by the supplemental air distribution system. The differences were determined to be solar effects. This conclusion was supported by observations in the fall crop during August. The trend of having elevated temperatures on the outer rows compared to the center row occurred in the eastern house both seasons, even though that greenhouse was the control house in the fall and the treatment house during the spring.

The primary impact on production from a transverse analysis was that higher yields occurred in the outer rows in both greenhouses (Figure 27). The reason was suspected to be the result of the increased light intensities on the outer rows compared to the inner rows. However, the difference in the cumulative yield between the greenhouses was not considered to be affected by this phenomenon, since the temperature differences at any correlating transverse locations were generally less than 1 °C throughout the season.

Economic Impacts

Yield Responses

The harvest period for the spring season was from April 16th through July 7th. The treatment house cumulatively produced 14% more yield than the control house (Figure 28), with a total of 4080 and 3570 kg, respectively. Return from the difference in

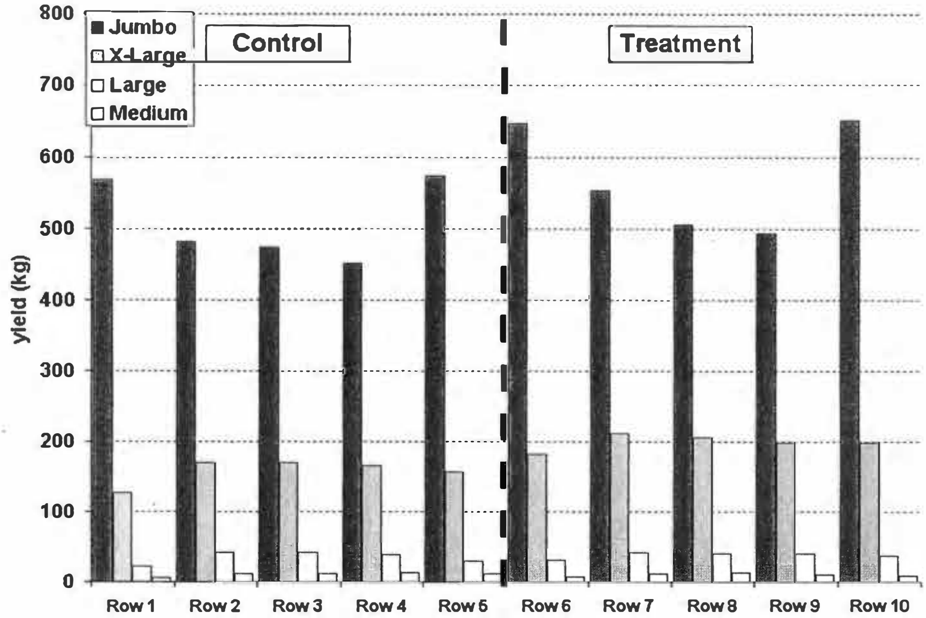


Figure 27. Spring yield by row and fruit size; row numbers increase from West to East.

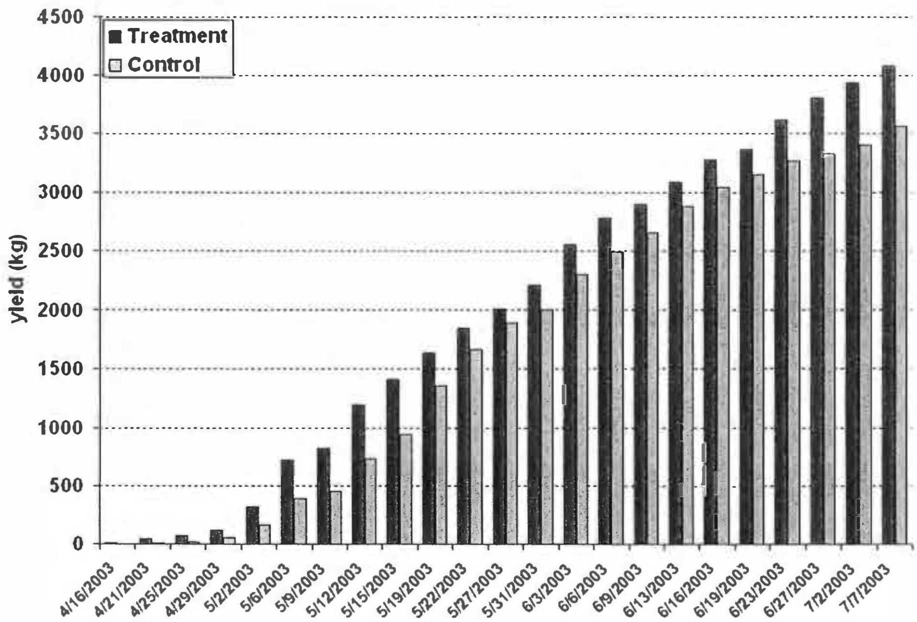


Figure 28. Cumulative spring yield.

yield equated to $1140 and was based upon a conservative wholesale price of $2.20 per kg. This estimate also does not reflect the advantages of an earlier harvest when producers can potentially obtain premium prices. The treatment house did experience an earlier yield than the control house. As of mid May, the treatment house produced 480 kg more than the control.

Energy Consumption - Fuel

The treatment house used 9% less fuel for heating during the spring season. The treatment house burned 7,380 liters of propane, while the control house burned 8,130 liters. The reduce fuel consumption resulted in a savings of $177 for the season based upon a propane price of $0.25 per liter.

The reduction in fuel use was due to the supplemental air distribution system transporting the heated air from above the foliage to within the dense foliage. Since the heater thermostats were located in the center of the house and engulfed by the canopy, the system provided a direct path for the warm air to reach the thermostats, thus interrupting the heating cycle quicker than in the control house. Figure 29 illustrates the difference in heating cycles between the houses. Temperature data at the thermostat was collected every minute from midnight to noon and then plotted to evaluate the heat cycling. The concept is clearly seen in the figure of how the treatment house is easily reaching the cutoff temperature at the thermostats, causing several heating cycles to occur during the night. The heater in the control house was operating at 100% duty cycle until after sunrise.

It is probable that further reductions in fuel consumptions could be achieved with a few adjustments and modifications. One adjustment would be to decrease the heating

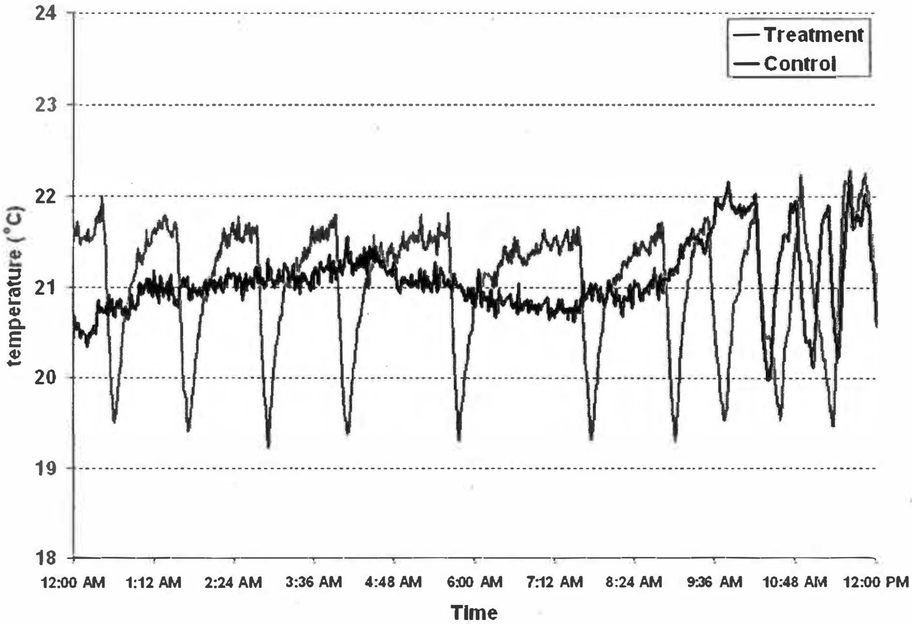


Figure 29. Temperature trends indicating heat cycling over 12-hr period on March 27th.

set point in the treatment house. The lower setting is justified from the evaluation of vertical temperature gradients during February. Temperatures increased with height in both houses, but the treatment house was 1.6 °C warmer than the control house at Level 1 during the nighttime of February, as shown in Figure 9a. Therefore, the heating set point in the treatment house could be reduced to equalize the minimum temperatures experienced between the greenhouses. Also, the height of the fan intake pipes could be increased from 2.4 m to 3.0 m to take in warmer air. Figure 9 indicates warmer nighttime temperatures at Level 5 (3.0 m) than at Level 4 (2.4 m). Lastly, fans with higher airflow rates could be selected to expel air through the perforated ducts. In this study, only the minimum accepted air circulation rate was achieved. Bailey (1973) suggested that higher airflow rates could further reduce the temperature drop of the air inside the duct, thus reducing longitudinal gradients.

Energy Consumption - Electricity

The electricity usage in the spring season was 7,160 and 3,610 kWh in the treatment and control houses, respectively. The increased electricity usage resulted in an additional cost of $243, based on $0.068 per kWh. The difference of 3,550 kWh equated to 22 kWh per day. The theoretical amount of electricity required to operate all five 225-watt fans for the air distribution system for 24 hours equaled 27 kWh per day. Potential reasons for the difference from the theoretical may be attributed to the system reducing the duty cycles of the heaters and/or ventilation fans or the system was using less than the theoretical estimate.

Though the supplemental air distribution system operated continuously throughout the growing season, the environmental evaluations revealed that the system was only beneficial during heating modes and during daylight hours when ventilation was minimal. Therefore, it is hypothesized that the full potential benefits from the system could be realized by only operating during heating modes and during the daytime of cooler months. The electricity cost could be substantially reduced by the selective operational periods of the system.

Overall Economic Impact

Most greenhouse tomato producers in Tennessee only grow a spring crop because yields from fall crops are generally much lower and is not enough to justify the required time, effort, and fuel cost. Therefore, the analysis of the spring crop was based on growing only one crop per year. The costs of the system included the capital of the equipment and construction and the additional electricity cost to operate the system (Table 5). The capital was based on an amortization at 10% over an estimated 5-year life,

Table 5. Price list for constructing supplemental air distribution system for a 9 x 29-m greenhouse for tomato production; items based on English units.

Item	Unit price		Quantity	Total
4C445 industrial blower	$100.05		5	$500.25
5' x 8" vent pipe	$7.97		5	$39.85
8" vent pipe cap	$3.63		5	$18.15
7" vent pipe cap	$4.66		5	$23.30
plastic pipe strap	$0.10	per foot	10	$1.00
polytube - 10" (layflat), 6 mil	$65.00	per 1000'	0.5	$32.50
4' x 8' x 3/4" plywood (sheathing)	$14.97		0.3125	$4.68
High-tensile wire	$4.00	per 100'	5	$20.00
6" lag eye bolts	$0.49		10	$4.90
tensioner	$4.00		5	$20.00
36" cable ties	$5.47	per 24	2	$10.94
5" gutter screws	$6.47	per 10	3	$19.41
1/2" wood screws	$0.83	per 10	2	$1.66
#8 1" bolts and nuts	$3.86	per 100	0.2	$0.77
lock washers	$2.18	per 80	0.25	$0.55
TOTAL ==>				**$697.96**

which equated to $178 per year. The cost of electricity was $243 per year. Returns from the difference in yield equated to $1140. Decreased propane consumption resulted in a savings of $177 per year. The net benefit of the supplemental air distributions system was $896 per year, and the benefit/cost ratio was 3.1.

Chapter 4 – Conclusions

Two greenhouses were operated for an entire spring season, the experimental treatment house had a supplemental air distribution system and the control house did not.

Evaluation of the vertical temperature and relative humidity gradients revealed that the supplemental air distribution system was most effective during periods of supplemental heating, which primarily occurred during nighttime. It was shown that the system successfully reduced the vertical gradients by moving warmer air from above to within the canopy. This reduction in gradient kept the canopy in the treatment house at lower relative humidity, reducing the susceptibility to infection from fungal diseases. Vertical relative humidity gradients were found to be primarily influenced by temperature rather than the moisture content of the air. This finding accentuates the importance of minimizing temperature gradients. Differences in temperature and relative humidity gradients between the greenhouses were negligible during periods not requiring supplemental heat.

Longitudinal temperature and relative humidity gradients were also found to be significantly reduced in the treatment house during periods of supplemental heating. It was shown that the air distribution system circulated the warm air accumulating on the southern end during heating modes, thus reducing the longitudinal temperature gradient. As before, relative humidity was primarily influenced by temperature. No statistically significant differences in the longitudinal gradients occurred between houses when supplemental heating was not required.

During periods of heavy heating, the transverse temperature gradient was significantly higher in the treatment house from the western side to the center. The increased gradient was due to the system fan intake location in the western row being directly in the path of the heated air stream, causing the warmest air to be directed through the canopy on that side. The system offered no benefit throughout the growing season in regard to transverse temperature gradients, but the gradients were not found to be a major problem in either greenhouse.

Nighttime vertical carbon dioxide gradients were reversed between greenhouses, with concentrations increasing with height in the treatment house. However, the concentrations above and within the canopy in the treatment house were both above the highest concentrations in the control house. This was suspected to be due to higher nighttime respirations rates induced by the additional air movement from the system. No significant carbon dioxide concentration differences were observed between the greenhouses during the daytime within the canopy.

An additional effect was suspected to occur during the daytime periods when ventilation was minimal. From the evaluation of the humidity ratios during February, 17% more moisture was in the air in the treatment house during the daytime. This difference was hypothesized to be due to increased transpiration rates induced by the additional air movement. This effect was only observed during low ventilation, probably because during heavy ventilation, the air movement from the system was considered negligible compared to the air movement induced by the ventilation fans.

The air distribution system was suspected to contribute to the increased yield compared to the control house. One reason was the significantly reduced nighttime relative humidity within the canopy in the treatment house, which was primarily influenced by temperature. A second reason for the increased yield was hypothesized to be the increased daytime transpiration rates in the treatment house during minimal ventilation. Also, it was suspected that accelerated ripening occurred as a result of the increased transpiration rate early in the season.

A reduction in fuel consumption was another benefit attributed to the air distribution system. It was shown that the system forced warmer air through the canopy during periods of heating, allowing the thermostat to reach the cutoff temperature faster than the control house. Therefore, the heater duty cycle in the treatment house was lower than in the control house, resulting in a 9% reduction in propane consumption.

The treatment house experienced a cumulative yield increase of 14% compared to the control house, with a difference of 518 kg. The fruit sizes between greenhouses were not significantly different.

The supplemental air distribution system was found to have benefit/cost ratio of 3.1, with a net return of $896. The components of the economic analysis included the yield increase and reduced fuel consumption, and the capital and electricity costs. The net return could be increased by reducing the electrical cost of the system by only operating the system during heating modes and during daytime periods of minimal ventilation, which appeared to be the times at which the system had greatest impact. Also, decreasing the heating set point, increasing the height of the intake pipes, and/or selecting fans with higher airflow rates for the system may further conserve fuel consumption.

List of References

ASAE Standards, 49th Ed. 2002. EP406.3. Heating, Ventilating, and Cooling Greenhouses. St. Joseph, Mich.: ASAE.

Bailey, B. J. 1973. The design of ducted-air heating systems. *ACTA Horticulturae* 46: 41-54.

Bakker, J. C. 1990. Effects of day and night humidity on yield and fruit quality of glasshouse tomatoes (*Lycopersicon esculentum* Mill.). *Journal of Horticultural Science* 65(3): 323-331.

Bakker, J. C. 1995. Greenhouse climate control: constraints and limitations. *ACTA Horticultura* 399: 25-35.

Bauerle, W. L., and R. H. Short. 1984. An overview of the North American greenhouse industry. *ACTA Horticulturae* 148: 43-48.

Buschermohle, M. J., and G. F. Grandle. 2002. Controlling the environment in greenhouses used for tomato production. Pub. No. W017. University of Tennessee Agricultural Extension Service.

Charles, W. B. and R. E. Harris. 1972. Tomato fruit-set at high and low temperatures. *Canadian Journal of Plant Science* 52: 497-506.

Cockshull, K. E. 1992. Crop environments. *ACTA Horticulturae* 312: 7-85.

Dane, F., Hunter, A. G., and O. L. Chambliss. 1991. Fruitset, pollen fertility, and combining ability of selected tomato genotypes under high-temperature field conditions. *Journal of the american Society for Horticultural Science* 116: 906-910.

Dodson, J, Gabor, B., Himmel, P., Kao, J., Stravato, V., Watterson, J., and W. Wiebe. 1997. Tomato Diseases: A Practical Guide for Seedsmen, Growers and Agricultural Advisors, Ed. B. Gabor, W. Wiebe. Seminis Vegetable Seeds, Inc.

Germing, G. H. 1967. Influence of orientation and type of heating. *4e Congres International du Chauffage et de la Climatisation*, Paris.

Grange, R. I., and D. W. Hand. 1987. A review of the effects of atmospheric humidity on the growth of horticultural crops. *Journal of Horticultural Science* 62: 125-134.

Hoffman, G. J. 1979. Humidity. *In Controlled Environment Guidelines for Plant Research*, ed. T. W. Tibbits, T. T. Kozlowski. London: Academic Press.

Kamburg, M. 1997. Consumer Awareness Rising; Shoppers Looking for Homegrown Flavor Find it in hothouse Products. *The Packer* 5: sec. 7B.

King, E. 1962. Beeinflussing des bestandsklimas durch mattenkuhlung. *Gartenwelk* 62(18): 367-369.

Landsberg, J. J. 1975. Temperature effects and plant responses. In *Progress in Plant Biometeorology*, ed. L. P. Smith, 86-107. amsterdam: Sweets and Zeittinger.

Leonardi, C., Guichard, S., and N. Bertin. 2000. High vapour pressure deficit influences growth, transpiration, and quality of tomato fruits. *Scientia Horticulturae* 84: 285-296.

Lucier, G., Lin, B., Allshouse, J., and L. S. Kantor. 2000. Factors Affecting Tomato Consumption in the United States. Economic Research Service/USDA. *Vegetables and Specialties* November: VGS-282.

Menses, J. F., and A. A. Monteiro. 1990. Ducted-air heating systems in greenhouses: experimental results. *ACTA Horticulturae* 263: 285-292.

Moroto, J. V., Bardisi, A., Lopez, S., Pascual, B., and J. Alagarda. 1995. Influence of relative humidity in the appearance of cracking in tomato (*Lycopersicon esculentum* Mill.) Fruit. *ACTA Horticulturae* 412: 306-312.

Straw, R. A. 2003. Personal communication.

Teitel, M., Segal, I., Shkylar, A., and M. Barak. 1999. A comparison between pipe and air heating methods for greenhouses. *Journal of Agricultural Engineering Research* 72: 259-273.

Tuzel, Y., Eltez, R. Z., and O. Altin. 1999. Effects of different pollination and fruit set practices on long season tomato production in glass houses. *Cahiers Options Mediterraneennes* 31: 391-396.

Walker, J. N. 1967. Ventilation and air movement in greenhouses. *4e Congres International du Chauffage et de la Climatisation*, Paris.

Walker, J. N., and G. A. Duncan. 1974. Effectiveness of recommended greenhouse air circulation systems. *Transactions of the ASAE* 17: 371-374.

Wells, C. M., and N. D. amos. 1994. Design of air distribution systems for closed greenhouses. *ACTA Horticulturae* 361: 93-104.

Went, F. W., and L. Cospar. 1945. Plant growth under controlled conditions. VI. Comparison between field and air conditioned greenhouse culture of tomatoes. *american Journal of Botany* 32: 643-654.

Whipps, J. M., and S. P. Budge. 2000. Effect of humidity on develop. m.ent of tomato powdery mildew (*Oidium lycopersici*) in the glasshouse. *European Journal of Plant Pathology* 106: 395-397.

Willits, D. H., and M. M. Peet. The effect of night temperature on greenhouse grown tomato yields in warm climates. *Agricultural and Forest Meteorology* 92: 191-202.

Witter, S. H. and L. H. Aung. 1969. Lycopersicon esculentum Mill. In *The Induction of Flowering*, ed. L. T. Evans. Macmillan of Austrailia.

Appendices

Appendix A – Discharge Uniformity of Perforated Duct

Colin M. Wells and Nevin D. Amos wrote a paper in 1994 titled *Design of Air Distribution Systems for Closed Greenhouses*. The objective addressed was to design an optimum air ventilation system with the use of perforated polyethylene ducting for cooling or heating the environment. The problem was to minimize the variability of discharge along the length of the duct while maintaining constant perforation spacing.

The approach was to step through a procedure or method for the duct design based on mathematical equations of airflow through a duct. The fundamental airflow equations were:

$$Q_o = \sum_{i=1}^{n} \left(C_{di} a_i \sqrt{\frac{2p_i}{\rho}} \right) \tag{1}$$

where: Q_o = total airflow in duct (m^3/s)

n = number of perforations in duct

C_{di} = discharge coefficient of perforation

a_i = area of a single perforation (m^2)

p_i = static pressure inside duct (Pa)

ρ = density of air (1.2 kg/m^3)

$$Q_o = CA\sqrt{\frac{2p_o}{\rho}} \tag{2}$$

where: C = overall discharge coefficient of the duct

A = cross sectional area of duct (m^2)

p_o = static pressure at duct entrance (Pa).

Equation 2 originated from Bernoulli's equation, and the overall discharge coefficient (C) has been estimated by non-linear regression to be a function of the aperture ratio (na/A) and the ratio of the duct length to the duct diameter (L/D) which is as follows:

$$C = 0.1077 + 0.6424\left(\frac{na}{A}\right)^{1.634} - 0.001402\left(\frac{na}{A}\right)^{2.49}\left(\frac{L}{D}\right)^{0.793} \qquad (3)$$

The authors reported that this empirical model has and R-squared value of 0.997 and was validated by 672 simulation runs. The overall discharge coefficient was calibrated for various ranges of duct parameters such as length, duct diameter, perforation diameter, number of perforations per row, and number of rows.

In the present study, the airflow rate through the duct (Q_o) was determined to be 0.206 m^3/s, based upon the minimum requirement of 15 air exchanges per hour within the tomato canopy. The design static pressure inside the duct (p_i) was 75 Pa. The diameter of each perforation was 0.010 m and was selected based on standard available hole-punch sizes. The average discharge coefficient for each perforation (C_{di}) was assumed to be 0.69, which was estimated for a submerged sharp-edged orifice. The total number of perforations was then calculated from rewriting Equation 1 as:

$$n = \left(\frac{4Q_o}{C_{di}\pi d^2}\right) * \sqrt{\frac{\rho}{2p_i}} \qquad (4)$$

where d is the diameter of each perforation in meters. The number of perforations (n) was calculated to be 376.

Once completed, the aperture ratio and the inlet static pressure were checked. The acceptable range for the aperture ratio is less than 1.5 and the inlet static pressure should be greater than 25 Pa to insure proper duct inflation. The aperture ratio was calculated to be 1.3. In order to check the inlet static pressure from Equation 2, the overall discharge coefficient (C) had to be determined from Equation 3. The duct length (L) was 25.3 m, which was equal to the length of the plant row, and a duct diameter (D) of 0.16 m was selected. The overall discharge coefficient was then calculated to be 0.96. Finally, the static pressure at the duct entrance (p_o) was calculated to be 67 Pa.

The longitudinal spacing of the perforations was based upon punching four rows of perforations for a length of 25.3 m, which resulted in a spacing of 0.27 m along the length.

The duct was constructed according to the theoretical outputs, and a pitot tube was used to measure the internal static pressure at the duct wall. Measurements were taken every 1.6 m along the length, and a coefficient of variation of 4.9 was achieved along the duct (Figure A1). The observed average static pressure inside the duct was77 Pa, and the observed static pressure at the duct entrance was 70 Pa.

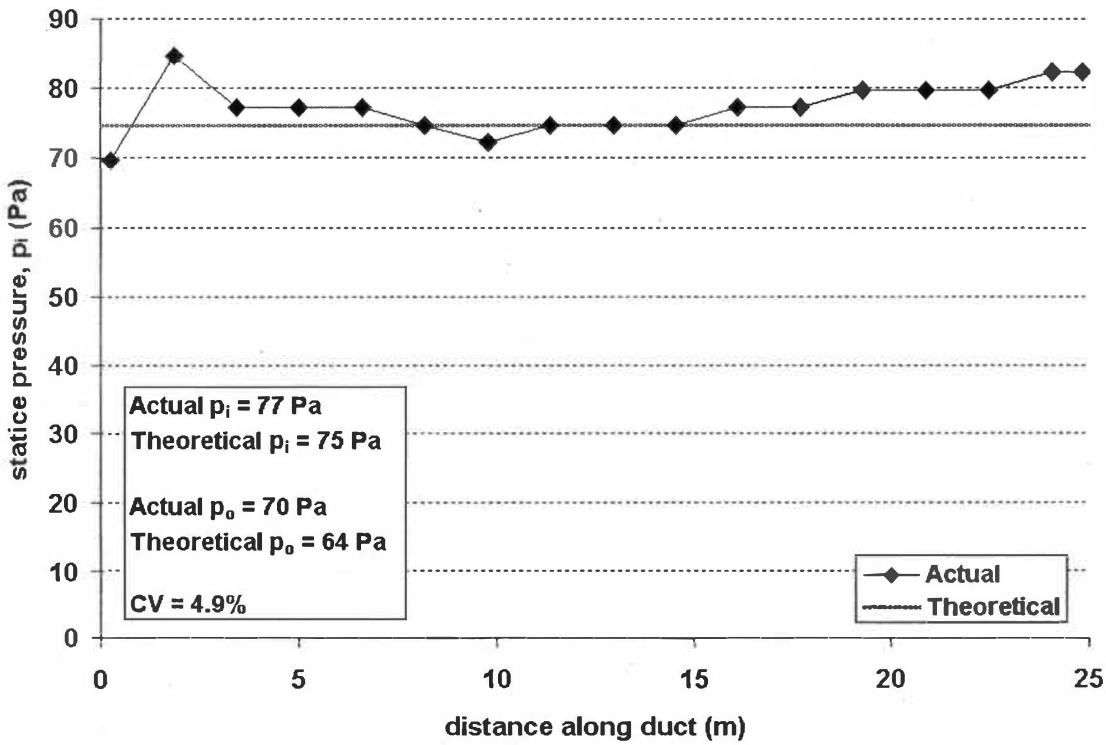


Figure A1. Actual versus theoretical static pressure along perforated duct.

Appendix B – Tabulated Environmental Data for Spring

Table B1. Nighttime vertical temperature gradients.

Month	Zone	Treatment	Δ Temp. through Zone (Δ °C)	Gradient Value (Δ °C/m)	Significance Pr > / t /
February	Zone 1	Treatment	0.4	0.6	<0.0001
		Control	1.4	2.3	
	Zone 2	Treatment	0.5	0.8	0.0054
		Control	1.0	1.6	
	Zone 3	Treatment	0.7	1.1	0.0432
		Control	0.9	1.5	
	Zone 4	Treatment	0.8	1.3	n.s.
		Control	1.0	1.6	
	Entire Zone	Treatment	2.3	1.0	
		Control	4.3	1.8	
March	Zone 1	Treatment	0.3	0.5	<0.0001
		Control	1.2	2.0	
	Zone 2	Treatment	0.5	0.8	<0.0001
		Control	0.9	1.4	
	Zone 3	Treatment	0.6	0.9	n.s.
		Control	0.6	1.0	
	Zone 4	Treatment	0.6	1.1	0.0456
		Control	0.8	1.3	
	Entire Zone	Treatment	2.0	0.8	
		Control	3.5	1.4	
April	Zone 1	Treatment	0.1	0.1	0.0029
		Control	0.3	0.4	
	Zone 2	Treatment	0.2	0.3	<0.0001
		Control	0.6	1.0	
	Zone 3	Treatment	0.5	0.9	n.s.
		Control	0.4	0.7	
	Zone 4	Treatment	0.5	0.8	n.s.
		Control	0.5	0.9	
	Entire Zone	Treatment	1.2	0.5	
		Control	1.8	0.7	
June	Zone 1	Treatment	-0.1	-0.2	0.0015
		Control	-0.2	-0.3	
	Zone 2	Treatment	-0.1	-0.2	n.s.
		Control	-0.1	-0.2	
	Zone 3	Treatment	-0.1	-0.2	<0.0001
		Control	0.0	0.0	
	Zone 4	Treatment	0.1	0.1	n.s.
		Control	0.1	0.2	
	Entire Zone	Treatment	-0.3	-0.1	
		Control	-0.2	-0.1	
July	Zone 1	Treatment	-0.1	-0.2	<0.0001
		Control	-0.2	-0.4	
	Zone 2	Treatment	-0.2	-0.3	n.s.
		Control	-0.2	-0.3	
	Zone 3	Treatment	-0.1	-0.2	n.s.
		Control	-0.1	-0.2	
	Zone 4	Treatment	0.1	0.1	n.s.
		Control	0.0	0.1	
	Entire Zone	Treatment	-0.3	-0.1	
		Control	-0.4	-0.2	

Table B2. Nighttime temperature deviations from heating set point (20 °C) at each vertical increment.

Month	Location	Treatment	Temp. deviation from 20 °C	Significance Pr > / t /
February	Level 1	Treatment	0.40	0.0123
		Control	-1.22	
	Level 2	Treatment	0.79	n.s.
		Control	0.17	
	Level 3	Treatment	1.30	n.s.
		Control	1.13	
	Level 4	Treatment	1.95	n.s.
		Control	2.07	
	Level 5	Treatment	2.75	n.s.
		Control	3.06	
March	Level 1	Treatment	0.33	0.0215
		Control	-0.25	
	Level 2	Treatment	0.62	n.s.
		Control	0.96	
	Level 3	Treatment	1.12	0.0001
		Control	1.82	
	Level 4	Treatment	1.68	<0.0001
		Control	2.45	
	Level 5	Treatment	2.33	<0.0001
		Control	3.24	
April	Level 1	Treatment	0.54	0.0240
		Control	0.12	
	Level 2	Treatment	0.63	n.s.
		Control	0.38	
	Level 3	Treatment	0.79	n.s.
		Control	0.96	
	Level 4	Treatment	1.31	n.s.
		Control	1.38	
	Level 5	Treatment	1.78	n.s.
		Control	1.91	
June	Level 1	Treatment	1.99	n.s.
		Control	1.44	
	Level 2	Treatment	1.89	n.s.
		Control	1.27	
	Level 3	Treatment	1.77	n.s.
		Control	1.15	
	Level 4	Treatment	1.65	n.s.
		Control	1.15	
	Level 5	Treatment	1.73	n.s.
		Control	1.24	
July	Level 1	Treatment	2.90	n.s.
		Control	2.19	
	Level 2	Treatment	2.80	n.s.
		Control	1.96	
	Level 3	Treatment	2.64	n.s.
		Control	1.81	
	Level 4	Treatment	2.51	n.s.
		Control	1.71	
	Level 5	Treatment	2.56	n.s.
		Control	1.76	

Table B3. Nighttime vertical relative humidity gradients.

Month	Zone	Treatment	Δ RH through Zone (Δ %)	Gradient Value (Δ %/m)	Significance Pr > / t /
February	North End	Treatment	-3	-1.9	<0.0001
		Control	-14	-7.7	
	South End	Treatment	-4	-2.4	0.0072
		Control	-10	-5.4	
March	North End	Treatment	-2	-1.1	<0.0001
		Control	-13	-7.1	
	South End	Treatment	-5	-2.7	0.0002
		Control	-8	-4.2	
April	North End	Treatment	2	1.1	<0.0001
		Control	-5	-3.2	
	South End	Treatment	-1	-0.4	n.s.
		Control	-2	-1.4	
June	North End	Treatment	3	2.3	<0.0001
		Control	0	0.1	
	South End	Treatment	4	2.9	<0.0001
		Control	3	1.9	
July	North End	Treatment	2	1.7	<0.0001
		Control	0	0.1	
	South End	Treatment	4	2.9	0.0014
		Control	2	1.7	

Table B4. Nighttime relative humidity values at each sensor location.

Month	Location	Treatment	Relative humidity (%)	Significance Pr > / t /
February	North-Bottom	Treatment	82	n.s.
		Control	82	
	North-Top	Treatment	77	0.0147
		Control	63	
	South-Bottom	Treatment	76	0.0307
		Control	69	
	South-Top	Treatment	70	0.0073
		Control	56	
March	North-Bottom	Treatment	91	0.0001
		Control	96	
	North-Top	Treatment	88	0.0018
		Control	79	
	South-Bottom	Treatment	85	0.0212
		Control	80	
	South-Top	Treatment	78	0.0031
		Control	71	
April	North-Bottom	Treatment	93	<0.0001
		Control	99	
	North-Top	Treatment	95	n.s.
		Control	92	
	South-Bottom	Treatment	86	n.s.
		Control	88	
	South-Top	Treatment	85	n.s.
		Control	85	
June	North-Bottom	Treatment	95	<0.0001
		Control	99	
	North-Top	Treatment	100	0.0056
		Control	99	
	South-Bottom	Treatment	93	<0.0001
		Control	95	
	South-Top	Treatment	98	n.s.
		Control	98	
July	North-Bottom	Treatment	97	<0.0001
		Control	100	
	North-Top	Treatment	100	n.s.
		Control	100	
	South-Bottom	Treatment	94	0.0028
		Control	96	
	South-Top	Treatment	99	n.s.
		Control	100	

Table B5. Nighttime vertical carbon dioxide gradients.

Month	Treatment	ΔCO_2 conc through Zone (Δ ppm)	Gradient Value (Δ ppm/m)	Significance Pr > / t /
February	Treatment	11	6	<0.0001
	Control	-35	-19	
March	Treatment	26	14	<0.0001
	Control	-46	-25	
April	Treatment	26	18	<0.0001
	Control	-37	-26	
June	Treatment	23	16	<0.0001
	Control	-33	-23	
July	Treatment	23	16	<0.0001
	Control	-34	-24	

Table B6. Nighttime carbon dioxide concentrations above and below the canopy.

Month	Location	Treatment	CO_2 concentraion (ppm)	Significance Pr > / t /
February	Bottom	Treatment	578	n.s.
		Control	524	
	Top	Treatment	589	0.0030
		Control	489	
March	Bottom	Treatment	640	0.0130
		Control	606	
	Top	Treatment	665	<0.0001
		Control	561	
April	Bottom	Treatment	643	0.0320
		Control	607	
	Top	Treatment	669	<0.0001
		Control	569	
June	Bottom	Treatment	663	0.0064
		Control	624	
	Top	Treatment	685	<0.0001
		Control	590	
July	Bottom	Treatment	639	n.s.
		Control	598	
	Top	Treatment	662	n.s.
		Control	564	

Table B7. Daytime vertical temperature gradients.

Month	Zone	Treatment	Δ Temp. through Zone (Δ °C)	Gradient Value (Δ °C/m)	Significance Pr > / t /
February	Zone 1	Treatment	0. 3	0. 5	0.0016
		Control	0.5	0. 9	
	Zone 2	Treatment	0. 1	0. 2	0.0024
		Control	0. 3	0.5	
	Zone 3	Treatment	0. 2	0. 4	n.s.
		Control	0. 3	0. 4	
	Zone 4	Treatment	0. 3	0. 4	0.0058
		Control	0.5	0. 8	
	Entire Zone	Treatment	0. 9	0. 4	
		Control	1. 6	0. 6	
March	Zone 1	Treatment	1. 2	1. 9	n.s.
		Control	1.1	1. 8	
	Zone 2	Treatment	0. 0	-0.1	0.0004
		Control	0. 1	0. 2	
	Zone 3	Treatment	0. 3	0. 4	<0.0001
		Control	0. 1	0. 1	
	Zone 4	Treatment	0. 2	0. 4	<0.0001
		Control	0. 4	0. 7	
	Entire Zone	Treatment	1. 6	0. 7	
		Control	1. 7	0. 7	
April	Zone 1	Treatment	1. 2	2. 0	n.s.
		Control	1. 6	2. 7	
	Zone 2	Treatment	1. 4	2. 3	n.s.
		Control	1.1	1. 8	
	Zone 3	Treatment	-0. 3	-0. 4	n.s.
		Control	-0.1	-0. 2	
	Zone 4	Treatment	0. 2	0. 4	0.0015
		Control	0.5	0. 7	
	Entire Zone	Treatment	2. 6	1.1	
		Control	3. 0	1. 2	
June	Zone 1	Treatment	0. 4	0. 7	0.0280
		Control	0. 3	0.5	
	Zone 2	Treatment	1.1	1. 8	<0.0001
		Control	1. 9	3. 1	
	Zone 3	Treatment	1.1	1. 8	<0.0001
		Control	0.5	0. 8	
	Zone 4	Treatment	0. 0	0. 1	<0.0001
		Control	0. 2	0. 4	
	Entire Zone	Treatment	2. 6	1.1	
		Control	2. 9	1. 2	
July	Zone 1	Treatment	0. 4	0. 6	n.s.
		Control	0. 3	0.5	
	Zone 2	Treatment	0. 9	1. 5	n.s.
		Control	1. 2	2. 0	
	Zone 3	Treatment	1. 4	2. 3	n.s.
		Control	0. 9	1. 6	
	Zone 4	Treatment	-0. 3	-0.5	0.0002
		Control	0. 2	0. 3	
	Entire Zone	Treatment	2. 4	1. 0	
		Control	2. 6	1.1	

Table B8. Daytime temperature deviations from ventilation set point (24 °C) at each vertical increment.

Month	Location	Treatment	Temp. deviation from 20 °C	Significance Pr > / t /
February	Level 1	Treatment	-3.22	n.s.
		Control	-3.54	
	Level 2	Treatment	-2.94	n.s.
		Control	-3.01	
	Level 3	Treatment	-2.82	n.s.
		Control	-2.70	
	Level 4	Treatment	-2.57	n.s.
		Control	-2.45	
	Level 5	Treatment	-2.32	n.s.
		Control	-1.98	
March	Level 1	Treatment	-3.07	n.s.
		Control	-2.69	
	Level 2	Treatment	-1.89	n.s.
		Control	-1.60	
	Level 3	Treatment	-1.93	n.s.
		Control	-1.46	
	Level 4	Treatment	-1.67	n.s.
		Control	-1.38	
	Level 5	Treatment	-1.43	n.s.
		Control	-0.94	
April	Level 1	Treatment	-2.02	n.s.
		Control	-1.81	
	Level 2	Treatment	-0.83	n.s.
		Control	-0.18	
	Level 3	Treatment	0.59	n.s.
		Control	0.89	
	Level 4	Treatment	0.32	n.s.
		Control	0.74	
	Level 5	Treatment	0.55	n.s.
		Control	1.19	
June	Level 1	Treatment	1.08	n.s.
		Control	1.50	
	Level 2	Treatment	1.48	n.s.
		Control	1.79	
	Level 3	Treatment	2.58	0.0072
		Control	3.65	
	Level 4	Treatment	3.69	n.s.
		Control	4.17	
	Level 5	Treatment	3.73	n.s.
		Control	4.42	
July	Level 1	Treatment	1.29	n.s.
		Control	1.28	
	Level 2	Treatment	1.65	n.s.
		Control	1.61	
	Level 3	Treatment	2.54	n.s.
		Control	2.80	
	Level 4	Treatment	3.96	n.s.
		Control	3.74	
	Level 5	Treatment	3.65	n.s.
		Control	3.90	

Table B9. Daytime vertical relative humidity gradients.

Month	Zone	Treatment	Δ RH through Zone (Δ %)	Gradient Value (Δ %/m)	Significance Pr > / t /
February	North End	Treatment	1	0.8	0.0006
		Control	-5	-2.5	
	South End	Treatment	-1	-0.7	<0.0001
		Control	-5	-2.8	
March	North End	Treatment	0	0.2	<0.0001
		Control	-3	-1.7	
	South End	Treatment	-3	-1.9	0.0014
		Control	-6	-3.1	
April	North End	Treatment	-3	-2.0	n.s.
		Control	-5	-3.5	
	South End	Treatment	-4	-3.1	n.s.
		Control	-6	-4.1	
June	North End	Treatment	0	0.3	<0.0001
		Control	-4	-3.1	
	South End	Treatment	-1	-1.0	<0.0001
		Control	-6	-4.2	
July	North End	Treatment	2	1.2	0.0020
		Control	-4	-2.6	
	South End	Treatment	0	0.0	0.0257
		Control	-5	-3.5	

Table B10. Daytime relative humidity values at each sensor location.

Month	Location	Treatment	Relative humidity (%)	Significance Pr > / t /
February	North-Bottom	Treatment	77	n.s.
		Control	74	
	North-Top	Treatment	79	n.s.
		Control	68	
	South-Bottom	Treatment	73	n.s.
		Control	67	
	South-Top	Treatment	79	n.s.
		Control	68	
March	North-Bottom	Treatment	77	n.s.
		Control	78	
	North-Top	Treatment	72	n.s.
		Control	60	
	South-Bottom	Treatment	75	n.s.
		Control	74	
	South-Top	Treatment	78	n.s.
		Control	73	
April	North-Bottom	Treatment	81	n.s.
		Control	82	
	North-Top	Treatment	77	n.s.
		Control	75	
	South-Bottom	Treatment	80	n.s.
		Control	80	
	South-Top	Treatment	74	n.s.
		Control	72	
June	North-Bottom	Treatment	82	n.s.
		Control	83	
	North-Top	Treatment	83	n.s.
		Control	77	
	South-Bottom	Treatment	81	n.s.
		Control	82	
	South-Top	Treatment	79	n.s.
		Control	74	
July	North-Bottom	Treatment	90	n.s.
		Control	94	
	North-Top	Treatment	93	n.s.
		Control	89	
	South-Bottom	Treatment	88	n.s.
		Control	91	
	South-Top	Treatment	88	n.s.
		Control	84	

Table B11. Daytime vertical carbon dioxide gradients.

Month	Treatment	Δ CO_2 conc Through Zone (Δ ppm)	Gradient Value (Δ ppm/m)	Significance Pr > / t /
February	Treatment	2	1	0.0001
	Control	-29	-16	
March	Treatment	-2	-1	<0.0001
	Control	-31	-17	
April	Treatment	-6	-4	<0.0001
	Control	-34	-24	
June	Treatment	-20	-14	<0.0001
	Control	-40	-28	
July	Treatment	-20	-14	0.0284
	Control	-40	-28	

Table B12. Daytime carbon dioxide concentrations above and below the canopy.

Month	Location	Treatment	CO_2 concentraion (ppm)	Significance Pr > / t /
February	Bottom	Treatment	444	n.s.
		Control	440	
	Top	Treatment	445	n.s.
		Control	411	
March	Bottom	Treatment	395	n.s.
		Control	398	
	Top	Treatment	393	0.0016
		Control	367	
April	Bottom	Treatment	392	n.s.
		Control	390	
	Top	Treatment	386	0.0003
		Control	355	
June	Bottom	Treatment	390	n.s.
		Control	388	
	Top	Treatment	370	<0.0001
		Control	348	
July	Bottom	Treatment	399	n.s.
		Control	399	
	Top	Treatment	380	n.s.
		Control	358	

Table B13. Nighttime longitudinal temperature gradients.

Month	Zone	Treatment	Δ Temp. through Zone (Δ °C)	Gradient Value (Δ °C/m)	Significance Pr > / t /
February	North to Center	Treatment	-0.1	0.0	n.s.
		Control	0.1	0.0	
	Center to South	Treatment	0.5	0.1	0.0074
		Control	1.5	0.2	
	Entire Zone	Treatment	0.4	0.0	
		Control	1.7	0.1	
March	North to Center	Treatment	-0.1	0.0	0.0003
		Control	0.0	0.0	
	Center to South	Treatment	0.7	0.1	<0.0001
		Control	1.8	0.2	
	Entire Zone	Treatment	0.6	0.0	
		Control	1.8	0.1	
April	North to Center	Treatment	-0.1	0.0	0.0011
		Control	0.2	0.0	
	Center to South	Treatment	1.1	0.2	n.s.
		Control	1.3	0.2	
	Entire Zone	Treatment	1.0	0.1	
		Control	1.5	0.1	
June	North to Center	Treatment	-0.1	0.0	n.s.
		Control	-0.1	0.0	
	Center to South	Treatment	0.0	0.0	n.s.
		Control	0.0	0.0	
	Entire Zone	Treatment	-0.1	0.0	
		Control	-0.1	0.0	
July	North to Center	Treatment	-0.1	0.0	n.s.
		Control	-0.1	0.0	
	Center to South	Treatment	0.1	0.0	n.s.
		Control	0.1	0.0	
	Entire Zone	Treatment	0.0	0.0	
		Control	0.1	0.0	

Table B14. Nighttime temperature deviations from the heating set point (20 °C) at all horizontal locations at 1.2-m height (mid-canopy).

Month	Location	Treatment	Temp. deviation from 20 °C	Significance Pr > / t /
February	North	Treatment	0.57	n.s.
		Control	-0.37	
	Center	Treatment	0.48	n.s.
		Control	-0.23	
	South	Treatment	0.96	n.s.
		Control	1.32	
	West	Treatment	1.21	n.s.
		Control	0.13	
	East	Treatment	0.71	n.s.
		Control	0.02	
March	North	Treatment	0.40	n.s.
		Control	0.33	
	Center	Treatment	0.26	n.s.
		Control	0.35	
	South	Treatment	0.97	<0.0001
		Control	2.11	
	West	Treatment	0.89	n.s.
		Control	1.03	
	East	Treatment	0.60	n.s.
		Control	0.97	
April	North	Treatment	0.44	0.0079
		Control	-0.13	
	Center	Treatment	0.33	n.s.
		Control	0.05	
	South	Treatment	1.47	n.s.
		Control	1.36	
	West	Treatment	0.36	n.s.
		Control	0.29	
	East	Treatment	0.54	n.s.
		Control	0.31	
June	North	Treatment	2.06	n.s.
		Control	1.46	
	Center	Treatment	2.01	n.s.
		Control	1.41	
	South	Treatment	2.03	n.s.
		Control	1.42	
	West	Treatment	1.57	n.s.
		Control	1.02	
	East	Treatment	1.77	0.0301
		Control	1.04	
July	North	Treatment	2.93	n.s.
		Control	2.11	
	Center	Treatment	2.89	n.s.
		Control	2.02	
	South	Treatment	2.96	n.s.
		Control	2.14	
	West	Treatment	2.53	n.s.
		Control	1.73	
	East	Treatment	2.66	n.s.
		Control	1.79	

Table B15. Nighttime longitudinal relative humidity gradients.

Month	Zone	Treatment	Δ RH Through Zone (Δ %)	Gradient Value (Δ %/m)	Significance Pr > / t /
February	North to South	Treatment	-6	-0.6	0.0414
		Control	-13	-1.4	
March	North to South	Treatment	-6	-0.6	<0.0001
		Control	-16	-1.7	
April	North to South	Treatment	-7	-0.7	0.0007
		Control	-11	-1.1	
June	North to South	Treatment	-3	-0.3	<0.0001
		Control	-4	-0.4	
July	North to South	Treatment	-3	-0.3	n.s.
		Control	-3	-0.4	

Table B16. Daytime longitudinal temperature gradients.

Month	Zone	Treatment	Δ Temp. through Zone (Δ °C)	Gradient Value (Δ °C/m)	Significance Pr > / t /
February	North to Center	Treatment	0.1	0.0	n.s.
		Control	0.4	0.1	
	Center to South	Treatment	0.8	0.1	n.s.
		Control	1.0	0.1	
	Entire Zone	Treatment	1.0	0.1	
		Control	1.5	0.1	
March	North to Center	Treatment	0.1	0.0	n.s.
		Control	0.3	0.0	
	Center to South	Treatment	1.0	0.1	n.s.
		Control	1.2	0.2	
	Entire Zone	Treatment	1.2	0.1	
		Control	1.5	0.1	
April	North to Center	Treatment	0.3	0.0	n.s.
		Control	0.3	0.0	
	Center to South	Treatment	0.1	0.0	n.s.
		Control	0.5	0.1	
	Entire Zone	Treatment	0.4	0.0	
		Control	0.8	0.1	
June	North to Center	Treatment	0.1	0.0	0.0014
		Control	-0.1	0.0	
	Center to South	Treatment	0.6	0.1	<0.0001
		Control	0.2	0.0	
	Entire Zone	Treatment	0.7	0.0	
		Control	0.1	0.0	
July	North to Center	Treatment	0.0	0.0	n.s.
		Control	0.0	0.0	
	Center to South	Treatment	0.6	0.1	0.0050
		Control	0.1	0.0	
	Entire Zone	Treatment	0.6	0.0	
		Control	0.1	0.0	

Table B17. Daytime temperature deviations from the ventilation set point (24 °C) at all horizontal locations at 1.2-m height (mid-canopy).

Month	Location	Treatment	Temp. deviation from 20 °C	Significance Pr > / t /
February	North	Treatment	-3.25	n.s.
		Control	-3.51	
	Center	Treatment	-3.14	n.s.
		Control	-3.09	
	South	Treatment	-2.36	n.s.
		Control	-2.09	
	West	Treatment	-3.23	n.s.
		Control	-3.17	
	East	Treatment	-2.69	n.s.
		Control	-3.20	
March	North	Treatment	-2.44	n.s.
		Control	-2.06	
	Center	Treatment	-2.29	n.s.
		Control	-1.79	
	South	Treatment	-1.29	0.0233
		Control	-0.57	
	West	Treatment	-2.25	n.s.
		Control	-1.99	
	East	Treatment	-1.20	n.s.
		Control	-1.60	
April	North	Treatment	-1.49	0.0080
		Control	-0.40	
	Center	Treatment	-1.17	0.0248
		Control	-0.12	
	South	Treatment	-1.02	0.0016
		Control	0.43	
	West	Treatment	0.06	n.s.
		Control	-0.57	
	East	Treatment	-0.51	n.s.
		Control	-0.24	
June	North	Treatment	0.78	0.0007
		Control	1.82	
	Center	Treatment	0.85	0.0024
		Control	1.73	
	South	Treatment	1.42	0.0463
		Control	1.95	
	West	Treatment	2.22	n.s.
		Control	1.82	
	East	Treatment	2.11	n.s.
		Control	1.65	
July	North	Treatment	1.11	n.s.
		Control	1.60	
	Center	Treatment	1.12	n.s.
		Control	1.57	
	South	Treatment	1.68	n.s.
		Control	1.71	
	West	Treatment	2.10	n.s.
		Control	1.57	
	East	Treatment	2.22	n.s.
		Control	1.59	

Table B18. Daytime longitudinal relative humidity gradients.

Month	Zone	Treatment	Δ RH through Zone (Δ %)	Gradient Value (Δ %/m)	Significance Pr > /.t /
February	North to South	Treatment	-4	-0.4	0.0111
		Control	-7	-0.8	
March	North to South	Treatment	-2	-0.2	0.0401
		Control	-4	-0.4	
April	North to South	Treatment	-1	-0.2	n.s.
		Control	-2	-0.2	
June	North to South	Treatment	-1	-0.2	n.s.
		Control	-1	-0.1	
July	North to South	Treatment	-2	-0.2	n.s.
		Control	-3	-0.3	

Table B19. Nighttime transverse temperature gradients.

Month	Zone	Treatment	□ Temp. through Zone (□ °C)	Gradient Value (□ °C/m)	Significance Pr > / t /
February	West to Center	Treatment	-0.7	-0.2	0.0082
		Control	-0.4	-0.1	
	Center to East	Treatment	0.2	0.1	n.s.
		Control	0.2	0.1	
	Entire Zone	Treatment	-0.5	-0.1	
		Control	-0.1	0.0	
March	West to Center	Treatment	-0.6	-0.2	n.s.
		Control	-0.7	-0.2	
	Center to East	Treatment	0.3	0.1	<0.0001
		Control	0.6	0.2	
	Entire Zone	Treatment	-0.3	-0.1	
		Control	-0.1	0.0	
April	West to Center	Treatment	0.0	0.0	0.0129
		Control	-0.2	-0.1	
	Center to East	Treatment	0.2	0.1	n.s.
		Control	0.2	0.1	
	Entire Zone	Treatment	0.2	0.0	
		Control	0.0	0.0	
June	West to Center	Treatment	0.4	0.1	n.s.
		Control	0.4	0.1	
	Center to East	Treatment	-0.2	-0.1	0.0004
		Control	-0.4	-0.1	
	Entire Zone	Treatment	0.2	0.0	
		Control	0.0	0.0	
July	West to Center	Treatment	0.4	0.1	n.s.
		Control	0.3	0.1	
	Center to East	Treatment	-0.2	-0.1	n.s.
		Control	-0.2	-0.1	
	Entire Zone	Treatment	0.2	0.0	
		Control	0.0	0.0	

Table B20. Daytime transverse temperature gradients.

Month	Zone	Treatment	□ Temp. through Zone (□ °C)	Gradient Value (□ °C/m)	Significance Pr > / t /
February	West to Center	Treatment	0.1	0.0	n.s.
		Control	0.1	0.0	
	Center to East	Treatment	0.5	0.2	0.0161
		Control	-0.1	0.0	
	Entire Zone	Treatment	0.5	0.1	
		Control	0.0	0.0	
March	West to Center	Treatment	0.0	0.0	0.0235
		Control	0.2	0.1	
	Center to East	Treatment	1.1	0.4	<0.0001
		Control	0.2	0.1	
	Entire Zone	Treatment	1.1	0.2	
		Control	0.4	0.1	
April	West to Center	Treatment	-1.2	-0.4	<0.0001
		Control	0.5	0.2	
	Center to East	Treatment	0.7	0.2	<0.0001
		Control	-0.1	0.0	
	Entire Zone	Treatment	-0.5	-0.1	
		Control	0.3	0.1	
June	West to Center	Treatment	-1.4	-0.5	<0.0001
		Control	-0.1	0.0	
	Center to East	Treatment	1.2	0.4	<0.0001
		Control	-0.1	0.0	
	Entire Zone	Treatment	-0.1	0.0	
		Control	-0.2	0.0	
July	West to Center	Treatment	-1.0	-0.3	0.0012
		Control	0.0	0.0	
	Center to East	Treatment	1.1	0.4	0.0010
		Control	0.0	0.0	
	Entire Zone	Treatment	0.1	0.0	
		Control	0.0	0.0	

Vita

Samuel Jason Ray was born in Opelika, AL on November 9th, 1973. At age seven, his family moved to rolling hills of Belvidere, TN, where he resided until graduating from Franklin County High School in 1992. He enlisted in the U. S. Air Force the following summer and served active duty as a computer operator until January 1996. After being honorably discharged, he embarked on his academic journey the following June. He was conferred an A. S. in pre-engineering in May 1999 from Motlow State Community College, and immediately transferred to The University of Tennessee in the Biosystems Engineering program. In December 2001, he received a B. S. with a concentration in Soil and Water. Directly afterwards, he was hired as a graduate research assistant and received a M. S. in Biosystems Engineering in May 2004.